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AFFDL-TR-74-136

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PHASE II DEVELOPMENT OF 1093°C (2000°F) PROTOTYPE MICROPHONE TRANSDUCER

KAMAN SCIENCES CORPORATION

TECHNICAL REPORT AFFDL–TR–74–136

FINAL REPORT FOR PERIOD NOVEMBER 1973 – SEPTEMBER 1974

DECEMBER 1974

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A program for the continued development of a 1093°C (2000°F) microphone system is described in the Final Report for Contract F33615-74-C-3011. The one year contract was issued to Kaman Sciences Corporation in Colorado Springs, Colorado by the Air Force Flight Dynamics Laboratory at Wright-Patterson AFB, Ohio in November of 1973. The report describes the objectives, goals and priorities of the research program. The analytical activities, experimental studies, system fabrication and design, performance testing, and extension of the

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) measuring technique to other measurands are presented. The program conclusions and recommendations are also discussed.

Two prototype microphone systems were designed and tested during the program. The standard microphone was designated as prototype 1, whereas prototype 2 featured a high sensitivity diaphragm design. A microphone design similar to that used for prototype 2 is recommended for any prototype production. Virtually all the program objectives and design goals were either achieved or significantly advanced from the previous effort under contract F33615-72-C-1199. Some of the observed characteristics of the microphone systems are as follows:

Operating Temperatures: 25°C to 1093°C (77 to 2000°F)

Dynamic Range: 100 dB (prototype 1)
120 dB (prototype 2)

Frequency Response: 2 to 10,500 Hertz (prototype 1) and 2 to 6880 Hertz (prototype 2) at 25°C.

2 to 8800 Hertz (prototype 1) and 2 to 6200 Hertz (prototype 2) at 1093°C.

Sensitivity Level: Prototype 1 (average 25 to 1093°C) - 117.6 dB
Prototype 2 (average 25 to 1093°C) - 107.8 dB
re 1 volt per microbar

Sensitivity Thermal Shift 4%maximum (prototype 1)
1.9% maximum (prototype 2)

Linearity: Within 2.8% (prototype 1)
Within 4.4% (prototype 2)

FORWORD

The research described in this report was performed by Kaman Sciences Corporation, Colorado Springs, Colorado, under Air Force Contract F33615-74-C-3011, Project 1472, "Dynamics Measuring and Analysis Technology for Military Vehicles," and Task No. 147201, "Dynamic Testing Procedures of Flight Vehicles," for the Dynamics Technology Applications Branch, Vehicle Dynamics Division, Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.

The work was administered by Mr. Donald E. Seely, (AFFDL/FYT), Project Engineer, of the Vehicle Dynamics Division.

John C. Schneider was the Program Manager and Richard K. Duke was the Project Engineer. Other members of the investigative team were John Cooney, Gene Hansen, Frank Hassey, Richard Denny, and Kenneth Morey.

This report covers work conducted from November 1973 to September 1974. This report was submitted by the authors on 30 September 1974.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

This final report covers efforts expended on Contract F33615-74-C-2011 with Air Force Flight Dynamics Laboratory/FYT, Air Force Systems Command at Wright-Patterson Air Force Base. Efforts of the program were directed toward producing prototype state-of-the-art aero-acoustic pressure transducers to operate at temperatures to 1093°C (2000°F). Such advancements are required to keep pace with the severe environments encountered in current aerospace programs.

A previous contract* demonstrated that the eddy-current transduction technique and materials selected for use at 1093°C could result in a working "breadboard" microphone system. The main purpose of the additional contract was to complete the design and testing of a working system, incorporate design improvements apparent from the first program and provide complete definition of the performance and expected service life characteristics.

Included in this report are the objectives, goals and priorities of the development program, the research efforts, the design and fabrication of the microphone system and its testing calibration and use. Extensions of the basic concept for use with other measurands as well as the program conclusions and recommendations are also presented.

* Contract F 33615-72-C-1199. The Final Report of these development activities is AFFDL-TR-73-62.

2.0 PROGRAM OBJECTIVES GOALS AND PRIORITIES

The main objective of the development program was to complete the design and testing of the "breadboard" microphone developed under Contract F 33615-72-C-1199 and to provide at least one finished prototype microphone system to the government. A second objective was to incorporate the minor changes in configuration, materials and assembly techniques which became apparent during the assembly and testing of the "bread-board" microphone developed under the previous contract. The final objective was to complete the definition of performance and service life characteristics versus temperature of the final microphone system.

The design goals of the program were unchanged from the first contract and were as follows:

1. The sensitivity of the element shall vary no more than ± 0.5% over the temperature range of -65°F to 2000°F.

2. The dynamic range of the element shall be at least 100 dB.

3. The transducing element output linearity shall be within ± 0.1% over the entire dynamic range.

4. The transducing element shall be insensitive, (less than 1%), to forces and motions other than those being measured.

5. The transducing element shall be insensitive, (less than 1%), to forces applied along any axis other than the sensing axis.

6. The element shall have a frequency response of 2-10,000 Hz (DC to 20,000 Hz is desired).

7. Output of the transducer element resulting from temperature transients of up to 5°F/second, over the temperature range specified in design goal 1, shall be less than 10 dB above the minimum output due to the inherent noise floor of the transducer.

8. The element shall have a high degree of stability with and without forcing function applied.

9. The element shall be sufficiently small in size to permit packaging in a 0.75 $in.^3$ transducer housing.

10. External power requirements of the element shall be held to a minimum.

11. The requirement for circuitry external to the transducing element shall also be held to a minimum.

12. The microphone transducer element shall have a 20-120 dB SPL and 90-190 dB SPL capability, re 20 micro Newtons per square meter (20 $\mu N/m^2$).

Priorities for competing design aspects of the microphone system were also to remain the same as those agreed to on Contract F33615-72-C-1199. The priorities were:

1. Operation to 1093°C(2000°F).
2. Response 2 to 10,000 Hz.
3. Dynamic Range 100 dB.
4. Thermal sensitivity shift less than ±0.5% over thermal environment.

3.0 DEVELOPMENT PROGRAM SUMMARY

To meet the objectives and goals of the continued development program, a detailed outline of the planned activities was originated. This program outline provided the basis for a systematic examination of development program problems. The program phases and tasks as outlined were as follows:

Phase I. Evaluation and Incorporation of Minor Improvements

- A. Analytical Evaluation
  1. Literature Survey Update
  2. Chemical Compatibility (Lifetime) Evaluation
  3. Sensor and Cable Geometry Evaluation
  4. Coil Geometry Evaluation
  5. Evaluation of Alternate Electronics
  6. Procurement of Materials for Subsequent Phases
- B. Report of Recommended Changes and Supporting Analytical Data
- C. Test Evaluation of Approved Recommended Improvements
  1. Fabrication of test hardware and specimens
  2. Chemical compatibility tests
  3. Coil geometry tests
  4. Sensor and cable component testing
  5. Electronics testing

Phase II. Design of Finished Prototype Microphone

- A. Report of Proposed Microphone Design
- B. Final System Design
  1. Sensor element design
  2. Packaging design
  3. Cabling design
  4. Electronics design

Phase III. Fabrication

A. Fabrication of Approved Design Hardware

B. Assembly of Microphone

Phase IV. Test and Evaluation

A. System Performance Comparison With Design Goals

1. Sensitivity testing from RT to 2000°F
2. Dynamic range testing
3. Output linearity tests
4. Sensitivity to extraneous forces and motions
5. Frequency response tests
6. Thermal transient effects on output
7. Stability tests without forcing function applied

B. Test Data Evaluation

1. Comparison of design goals and actual performance
2. Identification of areas of technology to be improved

C. Service Life vs. Temperature Estimate

1. Provide estimate of "expected life"
2. Identify degradation history of important performance parameters

Phase V. Extension Of Transducing Concept To Other Measurands

A. Accelerometer Concept

B. Pressure Transducer Concept

C. Force Transducer Concept

Phase VI. Delivery of Prototype Microphone For Independent Government Tests

A. Packaging and Shipment of Microphone to Government

Phase VII. Final Report

A. Prepare Draft of Final Report

B. Briefing at WPAFB

C. Prepare Final Report

4.0 ANALYTICAL EVALUATIONS

As was mentioned previously, analytical investigations of several areas were planned for Phase I of the program. The main emphasis of these investigations was to provide background and support data for recommended design changes in the microphone system which would improve the performance and/or ease of fabrication. The resulting recommendations were as follows:

1. Rhodium instead of platinum conductors should be used throughout the sensor and high temperature cable.

2. Silica beads rather than the wet extruded silica-magnesia insulation should be used for the high temperature cable mineral insulation.

3. Inconel 600 instead of platinum should be used for the high temperature cable sheath.

4. A cleanliness criteria, (such as Kaman's standard process), should be used to avoid any possible contamination of sensor components.

5. Low acid cements should be used. Several are available and were ordered for evaluation.

6. Design considerations should be reviewed to eliminate unnecessarily stressed regions of the sensor. This is especially important in the connection of the conductor leads to the coil wires.

7. Diaphragm design should be similar to the previous microphone. Preferred grain orientation in the fabrication of the diaphragm theoretically increases the allowable yield strength, thus increasing the thermal integrity and stability of the diaphragm.

8. Haynes Research Alloy #8077 should still be considered the standard sensor deflection material but other available dispersion strengthened superalloys should be tested for comparison.

9. A high temperature wave spring should be fabricated and tested for substitution of the more expensive thrust spring.

10. Pulsed TIG welding should be established as the welding technique to eliminate the "hot cracking" problems associated with LASER welding.

11. A porous metallic plug, (new to the design), should be added to prevent entry of undesired particles into the interior of the sensor.

12. Analyses showed that a coil of triangular cross section should not be used. Only slight variations of the rectangular cross section coil should be tested and used to increase coil sensitivity without adding excess capacitance.

13. A hybrid version of Kaman's standard KP-1910 electronics should be used for the electronics package. This represents considerable improvement in both size and performance over the previously used Lab-Vit electronics.

Specific details of each of these recommended changes are discussed in the following sections.

4.1 CHEMICAL COMPATIBILITY EVALUATION

One of the prime materials problems associated with the high temperature (2000°F) transducer is that of compatibility of the conductor wires with the surrounding media. This material must be a low resistivity (high conductivity) material, with good to excellent high temperature oxidation properties. Because only the noble elemental metals and particularly the platinum group fall into this category, they were extensively reviewed for potential problem areas and to determine the optimum material choice for the intended use. Alloys of the platinum metals group were also investigated.

4.1.1 Platinum Group Metals

The six platinum group metals are platinum, palladium, iridium, rhodium, ruthenium, and osmium. A listing of some of the more important physical properties of these metals and several others for comparison is shown in Table I and each is discussed further below.

Platinum metal is virtually non-oxidizable and is soluble only in liquids generating free chlorine, such as aqua regia. Certain phosphates attack platinum at high temperatures and care must be taken to avoid reducing conditions, particularly when compounds of arsenic, phosphorous tin, lead or iron are present. In addition, at red heat (≈1000°F) platinum is attacked by cyanides, sulfides and hydroxides.

Palladium is readily soluble in aqua regia and is attacked by boiling nitric and sulphuric acids. It is the lightest of the platinum metals group and also has the lowest melting point and highest resistivity of the group. Palladium also appears to be one of the more reactive of the platinum metals groups, forming several low melting point eutectics with various materials.

Iridium is one of the least corrodible of all the elements. It has a melting point higher than that of platinum and is only soluble in aqua regia when highly alloyed with platinum. It is also the least available of all the platinum group metals. The current Western World ouput is only about 1500 pounds per year as opposed to approximately 100,000 pounds per year for platinum. This metal has an excellent resistance to fused lead oxide, silicates, molten copper and iron at temperatures up to 1500°C. Additions of iridium to platinum considerably raise the corrosion resistance of platinum to a wide range of reagents.

TABLE 1. PHYSICAL PROPERTIES OF THE PLATINUM GROUP METALS AND SOME OF THE OTHER NOBLE METALS

	Atomic No.	Atomic Weight	Lattice Structure	Density (@ 20°C g/cc)	Melting Point (°C)	Thermal Conductivity (cgs units)	Specific Heat (cal/gm°C @ 20°C)	Temp. Coef. of Linear Expansion 0-100°C	Resistivity μΩ cm @ 20°C	Tensile Strength (Kpsi annealed)	Modulus of Elasticity (Tension - psi x 10^{-6}
Platinum	78	195.2	F.C.C.	21.4	1769	0.17	0.032	8.9 x 10^{-6}	10.6	17-23	25
Iridium	77	193.1	F.C.C.	22.4	2442	0.35	0.032	6.5	5.3	160	75
Osmium	76	190.2	C.P. Hex.	22.5	3000		0.031	6.6	9.5		81
Palladium	46	106.7	F.C.C.	11.9	1552	0.17	0.058	11.7	10.7	25	17
Rhodium	45	102.9	F.C.C.	12.4	1960	0.36	0.059	8.5	4.7	100	46
Ruthenium	44	101.7	C.P. Hex.	12.3	2250		0.031	9.6	9.5		60
Silver	47	107.8	F.C.C.	10.5	960.8	1.00	0.056	19.0	1.61	18	10.3
Gold	79	197.2	F.C.C.	19.3	1063	0.70	0.031	14.0	2.4	19	10.3
Copper	29	63.5	F.C.C.	8.9	1083	0.94	0.092	17.0	1.67	38	18

Rhodium's remarkable resistance to chemical attack surpasses that of platinum. It is impervious to caustic alkalis, acids and oxidizing agents including aqua regia. Rhodium also has the lowest resistivity of the platinum metals group and is less than one-half that of the platinum metal currently being used for the conductor leads.

Ruthenium and osmium are decidedly less noble than the other four metals of the platinum group. Both exist in numerous valency states and very readily form complexes, some of which are very volatile and poisonous.

4.1.2 Platinum Alloys

Platinum is generally alloyed with iridium, rhodium, ruthenium or nickel to increase its resistance to corrosion and to increase its mechanical properties. The increase in alloying additions however, have a strong tendency to increase the resistivity. Figure 1 illustrates the change in resistivity of platinum when alloyed with several materials. Some of the physical properties of the common platinum alloys are listed in Table 2 and general chemical data are presented below.

Rhodium is the preferred addition to platinum for most applications at high temperatures under oxidizing conditions. These additions provide improved mechanical properties and increase the resistance to corrosion. The 10% rhodium alloy is generally used more than any of the other alloys in this series. The platinum 10% rhodium alloy can be used for continuous service to 2600°F in oxidizing atmospheres provided it is properly insulated with aluminum oxide or another suitable high purity refractory. Platinum-rhodium alloys are used frequently in the glass industry because they withstand contact with molten glasses.

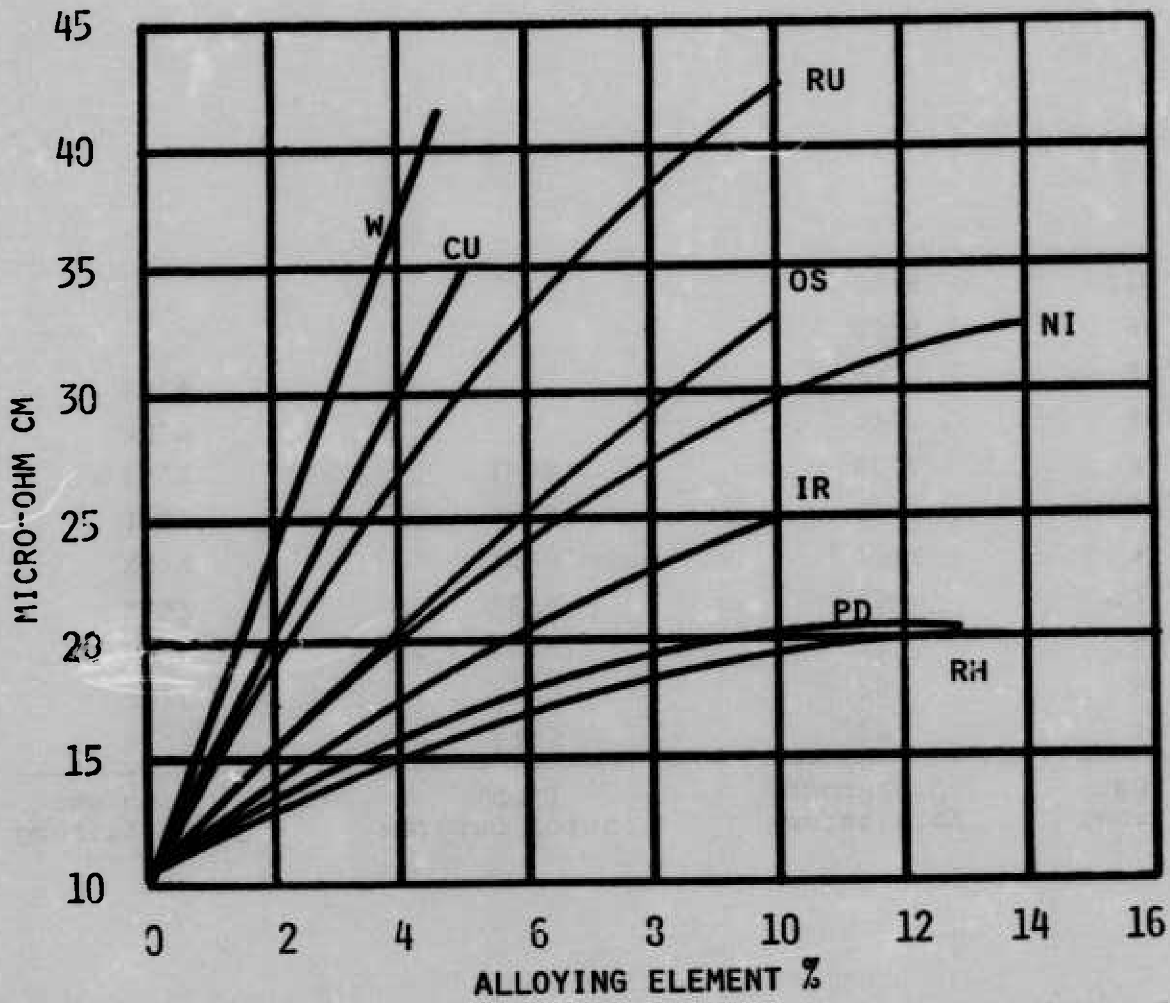

FIGURE 1 ELECTRICAL RESISTIVITY OF PLATINUM AT 68° F

TABLE 2. SOME PHYSICAL PROPERTIES OF PLATINUM GROUP ALLOYS

	Density @20°C (gm/cm^3)	Melting Point (0°C)	Resistivity μΩcm@20°C	Tensile Strength PSI (ann)
95 Pt/5 Ir.	21.5	1775	19	40,000
90 Pt/10 Ir.	21.5	1780	25	55,000
80 Pt/20 Ir.	21.6	1810	31	97,500
75 Pt/25 Ir.	21.7	1870	33	125,000
95 Pt/5 Rh.	20.7	1820	17.5	30,000
90 Pt/10 Rh.	19.9	1850	19.2	47,000
80 Pt/20 Rh.	18.7	1900	20.8	70,000
95 Pt/5 Ru.	20.7		31.5	60,000
90 Pt/10 Ru.	19.9		43	85,000
95 Pt/5 Ni.			23.6	93,000
90 Pt/10 Ni.			29.8	118,000

Iridium is also used as an addition to platinum to provide improved mechanical properties. It increases the resistance to corrosion while the alloy retains its workability. In general the corrosion resistance of the platinum-iridium alloys is excellent. The resistance to aqueous solutions of halogens and aqua regia increases with increasing iridium content.

Ruthenium 95% platinum alloy has essentially the same properties as the platinum 10% iridium alloy but it is not completely serviceable at high temperatures under strong oxidizing conditions.

Platinum-nickel alloys have long been used because of good strength at high temperatures however, selective oxidation of the nickel limits the use of these alloys at high temperatures under oxidizing conditions.

Under extreme oxidizing conditions the volatilization of platinum and its alloys when subjected to continuous operating temperatures may be substantially reduced by avoiding contact with oxygen. This can be achieved by completely embedding the metal in a high grade pure alumina refractory cement or block. Flame sprayed coatings, for example, are effective in preventing free circulation of air over the metal. Only high grade alumina, free from silica or other oxides, that are more easily reduced under reducing conditions should be employed, otherwise contamination and subsequent embrittlement of the platinum may result from a partial reduction of such oxides.

4.1.3 Discussion and Conclusions

Several conclusions were drawn from this study. The use of platinum alloys would increase the resistance to corrosion of the conductor wire but at a serious reduction in the performance of the unit because of the resistivity increases.

Only three of the metals in the platinum metals group remained for serious consideration. Iridium, because of its scarcity would be an unreasonable choice and because of the past experience with pure platinum, rhodium was chosen for investigation. The use of rhodium made sense for several reasons: rhodium is slightly more chemically inactive than platinum and may withstand the environments that platinum would not; rhodium is a better conductor than platinum and could provide better performance to the unit; and a rhodium-rhodium contact at wire junctions would be more compatible than the rhodium-platinum contact. The use of rhodium was not to be considered, however, without some careful considerations. The thermal coefficient of linear expansion of rhodium is less than that of platinum and considerably less than that of Inconel 600. Although in a previous contract cable failures involving the platinum wires were attributed to the differential thermal expansion of the platinum versus the Inconel 600, the failures observed were of a brittle nature, not a ductile fracture as one would expect from platinum. This indicates that had the platinum not become embrittled by some means, it would have withstood the stresses produced by the different expansivities. Further investigations were planned with different alloy systems to match more closely the thermal expansions.

Another area of concern was the fact that although it appears that the corrosion resistance of rhodium is superior to that of platinum, less information on rhodium's chemical compatibility is available in the literature. Because of this, the possibility of reactions occurring in the surrounding media should be minimized. Prior experiences with platinum indicated at least two possibilities; the first being reactions with moisture remaining in the silica-magnesia cable insulation after fabrication and the second the possibility of reactions with impurities in the same mixture. If both of the potential problem areas were eliminated, the possibilities for success would be increased.

If high purity silica beads were used in the cable both areas of concern would be minimized. The compatibility of rhodium with silicon is good to about 1389°C, above this temperature, melting of the eutectic grain boundaries has been observed. This applies only to pure silicon and not silica. No data have been found on the reaction kinetics of rhodium-silica.

Several other items were worthy of further investigations. The use of the phosphoric acid ceramic cements was questionable. This particular combination could contribute to the deterioration of a metal in contact with cements due to a liquid phase that is formed at the grain boundaries that have a high phosphorus content. Other low-acid or non-acid cements were available and procured for testing. Compatibility studies of these ceramic cements were also planned to determine the advantages or limitations of each material combination.

Another item planned was to maintain very close controls of the cleanliness of all parts being fabricated. Small amounts of impurities on the surface of components investigated could cause catastrophic damage at elevated temperatures. To present a chemically clean surface of platinum and its alloys after fabrication, pickling in hot concentrated hydrochloric acid to remove traces of iron or other contaminants was instigated. Passivation of other parts of the system such as the Inconel 600 was planned prior to final assembly to inhibit high temperature corrosion.

Lastly, the elimination of any stressed parts in the assembly was investigated. Stressed parts can contribute significantly to early failures. Stress combined with corrosive environments is extremely deleterious and causes effects analogous to aqueous stress corrosion in which an attack is accelerated at the grain boundaries.

4.2 SENSOR AND CABLE GEOMETRY STUDIES

4.2.1 Diaphragm Design

Since the microphone design completed at the close of Contract F33615-72-C-1199 represented several compromises between design and fabrication considerations, a re-evaluation of the design was felt to be appropriate. The concept review showed that for frequency response, the diaphragm should be thick and have a small diameter, since the natural frequency is a function of t/a^2, where t = diaphragm thickness and a = the diaphragm radius. For deflection and hence sensitivity, the diaphragm should be thin with a large diameter, since deflection is a function of a^4/t^3. Since these design factors compete for the choice of a and t, other practical aspects dictated the final decision. These practical restraints were:

1. Deflection of at least 0.0007 inches was needed for adequate sensitivity (60 to 80 dB dynamic range).

2. A button (thickened portion of the diaphragm) was required for proper electromagnetic coupling, (the thickness is a function of the resistivity of the diaphragm material).

3. Previous experience has shown that diaphragm thicknesses of less than 0.005 inches were impractical due to oxidation.

With these restraints and the one additional factor that the maximum allowable stress could not be exceeded, a diaphragm made from Haynes Research Alloy #8077 could be designed such that a dynamic range of 60 to 80 dB could be assured with the system having a natural frequency of approximately 8.2 kilohertz at 1093°C (2000°F). Additional dynamic range could be achieved with the use of electronic filtering to attenuate the resonant "spike". With this technique, the useful frequency range could be extended to within 90% of the natural frequency or approximately 7.4 kilohertz.

A final question involved the basic material properties and the extent to which the selection of a material might alter these design factors. An examination of the physical principles shows that a material with a high elastic modulus and yield strength would only slightly increase performance. For instance, a material with twice the elastic (Young's) modulus could only increase the natural frequency of the diaphragm by 10% with no loss of sensitivity. The stresses in such a diaphragm would require 1.6 times the yield strength of the comparative material; however, since even small improvements were of interest, material developments that would aid solving them were monitored. Since dispersion strengthened superalloys appear most suitable for use above 1093°C (2000°F), these developments were being monitored carefully. Three companies were presently known to be working with this type of material. They were:

Company	Developmental	Commercial
Sherritt-Gordon Mines LTD.	Ni-16Cr-5Al-$2ThO_2$	Ni-$2ThO_2$
International Nickel	Ni-20Cr-2.5Ti-1.5Al -1.13Y_2O_3	
Stellite Div. of Cabot	Ni-16Cr-4Al-1.5Y_2O_3	

The concern pointed out by the foregoing meager list was the unavailability of adequate materials. Of the entire list, only the Ni-$2ThO_2$ was commercially available in limited forms. Tests of these materials for use as diaphragm deflection members were planned for the experimental phase of the program.

4.2.2 High Temperature Spring

Since DS Nickel* (Ni-$2ThO_2$) was available in sheet stock the evaluation of a wave spring was planned for the experimental phase. Additional activities required to establish the usability of the wave spring were the location of an adequate and reasonable spring fabricator and the determination of the spring natural frequency.

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* Sherritt-Gordon Trademark. Equivalent to TD Nickel.

4.2.3 Cable Geometry

In light of other chemical compatability aspects, the use of pure silica beads was considered instead of the 98% silica-2% magnesia wet extruded mineral insulation. Using properly sized beads, the cable could be made in a process similar to the thermocouple cable fabricated at Kaman. This process would eliminate the undesirable water (hydroxides) and provide a cable that would be dimensionally stable at 1093°C. An alternate process was also planned. This process would use oversize 98% silica - 2% magnesia extruded insulation conductor wires that would be fixed and fired at 1093°F to provide the proper final insulator size. In the previous contract, shrinkage of the unfired insulation within the finished cable proved to be unsuitable.

4.2.4 Cable Conductors

As was previously indicated in the compatibility section, rhodium wire was recommended for the cable conductors. Factors influencing this recommendation were its apparent high chemical stability and corrosion resistance and its low electrical resistivity. Qualification tests for the wire were planned for the experimental phase of the program.

4.2.5 Welding Studies

Welding studies indicated that the "hot-cracking" problems experienced with LASER welding in earlier efforts could be alleviated by the use of pulsed tungsten-inert-gas (TIG) welding. With this process, the cooling of the molten weld region could be controlled by the proper selection of weld parameters. Welding tests using the pulsed TIG equipment were planned.

4.2.6 Porous Plug

Several vendors of fibrous or porous metals were contacted concerning the requirement for a filtered vent. Only one organization could provide a porous plug adequate for use at 1093°C. Further tests were planned for the experimental phase to determine whether an absolute or gage (dynamic fluctuations only) microphone sensor was necessary since the porous plug is only required for operation in the gage mode. The major disadvantage of the gage mode is that oxidation occurs inside as well as outside the transducer sensor.

4.3 COIL GEOMETRY EVALUATION

4.3.1 General Considerations

The eddy-current transduction principle is based upon the coupling of a coil to eddy-currents generated by the coil in a nearby conductive media. The degree of coupling affects the sensitivity of the transducer and is dependent upon such parameters as resistivity of the conductive media and coil wire, interwinding capacity, and geometry. The geometry of a flat (pancake) coil parallel and close to a flat conductive media offers a high degree of coupling. For ease of winding and fabrication, the coil is normally of a rectangular half-section with several layers of spiral wound coils contained within this rectangle. This geometry was not felt to be the optimum for the highest degree of coupling.

The coils used in the 1093°C (2000°F) microphone of the previous contract were of rectangular cross section. Coils of a non-rectangular cross-sectional configuration were fabricated and tested for general parameters and characteristics when spaced from a conductor at various distances. In general it was found that any increase of performance was not significant enough to warrant the more complex geometry and that changes would limit practical cable lengths.

4.3.2 Summary and Recommendations

Changing the coil configuration would result in a small increase of sensitivity but other drawbacks were introduced. Neither the rectangular nor alternate configurations were strictly optimum and yet another configuration might be better to satisfy the microphone requirements. This could be a larger diameter rectangular configuration, but in this case the capacity and resistance would be increased to further limit the cable length. The capacity could be decreased by using a thicker insulation on the wire but this would decrease the number of turns per unit cross sectional area which decreases inductance and sensitivity.

Since the cable length is of importance, it was decided that the presently used rectangular coil is close to the practical optimum and that designing some alternate configuration to further optimize sensitivity was not worthwhile since sensitivity would be increased by less than 2 dB. Only slight variations of the presently used coil were recommended for further investigation when designing and testing the coils under the experimental phase of the development program.

4.4 EVALUATION OF ALTERNATE ELECTRONICS

Since the signal conditioning electronics has a significant effect on the total system performance, changes of the electronics were a necessary part of the system development. Kaman has in production a new electronics package being marketed as part of the new KP-1910 series High Temperature Pressure Measuring System. This new electronics package offers the following advantages over the previous Lab-Vit electronics.

a) Smaller size

b) Lower temperature coefficients

c) Higher reliability

d) Minimized interaction between the Gain and Zero controls.

e) Larger output swings available within the limits of -9 to +10 Vdc.

f) Increased interchangeability, (a small printed circuit "bridge card" within the electronics housing contains all of the necessary compensation components. All components on this card are passive.)

g) Lower output impedance by approximately three orders of magnitude.

h) Allows higher output cable capacitance without affecting frequency response.

i) Two pole active filter output stage to reduce high frequency noise and carrier ripple.

j) Lower input supply current.

It was felt to be in the best interest of the Government to utilize some of the above advantages of an extensive Kaman funded development program; consequently, it was proposed that the microphone electronics be based upon the current KP-1910 design. The main emphasis of the program was to be an increase of the signal-to-noise ratio. Kaman expected difficulty achieving the desired 100 dB signal-to-noise ratio with any amplitude or phase demodulation system and the design goal was set to be a minimum of 80 dB with the purpose of achieving the most possible. A second goal of the program was an increase in the operating temperature range of the electronics beyond the 0 to 55°C range of the KP-1910. The third goal was the examination of the feasibility of an adjustable filter to attentuate the signal due to the resonant peak of the sensor diaphragm in order to increase the frequency response range of the system. This technique has been used successfully by Kaman to increase the frequency response of other instruments including a high temperature accelerometer.

The noise level reduction of the KP-1910 was split into two sections, oscillator noise and demodulator noise. The oscillator was to have extremely good amplitude stability because the system output stability is directly proportional to the amplitude stability of the oscillator. The requirement necessitates a very high gain in the oscillator control loop in order to maintain a stable amplitude with changing temperature. Noise in this high gain control loop appears as an amplitude modulation on the oscillator output and therefore is transmitted to the system output; hence, the oscillator noise level must be lower than the system noise level. Secondly, the noise level in the AC amplifier, the demodulator and its associated DC stages was to be less -80 dB or lower.

In general terms, the plan of this development was to identify the main contributors of noise in each section and to replace these with lower noise components.

5.0 EXPERIMENTAL STUDIES

Experimental studies, in support of the analytical investigations, were made to provide data for the selection of final microphone design parameters. A summary of the results of the experimental investigations were recommended as follows:

1. Chemical Compatability Tests
   a. Ceramic cement: Cotronics #901.
   b. Coil lead wire: 0.002 inch diameter rhodium coated with 0.0075 inch thickness Secon "E" insulation.
   c. Coil extension lead wires: 0.010 inch diameter platinum.
   d. Coil holder: to be fabricated from 94+% alumina.
   e. Ceramic feed-through tubing: 99+% alumina.
   f. High temperature cable conductors: 0.010 inch diameter rhodium.
   g. Cable insulation: pre-dried 98% silica-2% magnesia beads.
   h. Cable sheath material: Inconel Alloy 600.
2. Coil Geometry Tests
   a. Coil configuration: to a rectangular cross section.
   b. Rhodium buttons on the active and inactive diaphragm were to be used for inductive coupling on at least one prototype.
3. Sensor Components Tests
   a. Haynes research alloy #8077 was identified as the best material for use as a diaphragm. Inconel Alloy MA 753 was selected as the back-up material.
4. High Temperature Spring Tests
   a. A wave spring fabricated from DS Nickel was to be used to replace the thrust spring.

5. Material Shrinkage Tests
   a. Coil forms were to be made from oversized alumina stock and fired at 1200°C (2192°F) to provide dimensional stability.
   b. Cable insulation beads fabricated from 98% silica-2% magnesia were to be fired at 1204°C (2200°F) to eliminate moisture and provide dimensional stability.
6. High Temperature Cable Differential Thermal Expansion Tests
   a. Rhodium wire and Inconel Alloy 600 sheath material were selected for the cable.
7. Welding Studies
   a. Haynes research alloy #8077 was selected for the sensor case since hermetic laser welding was possible.
8. Porous Filter Evaluation
   a. Since hermetic welding was possible, the use of a filtered vent was not considered necessary. A suitable porous plug was commercially available.
9. Electronics Studies
   a. A low-noise version of the KP-1910 electronics with greater than 80 dB signal-to-noise ratio was to be used.
   b. A switchable output was to allow use in either the AC or DC coupled mode.

Details of the experimental studies leading to these recommended final design features are discussed in the following sections of the report.

5.1 MATERIAL CHEMICAL COMPATIBILITY TESTS

Research was performed to substantially reduce or eliminate the problems associated with chemical reactivity of certain materials used in the 1093°C (2000°F) transducer.

The initial goal was the solution of two specific problems:

1) An apparent chemical incompatibility at 2000°F of the conductor wire with the insulation used in the cable assembly.

2) Incompatibility at 2000°F of ceramic adhesive cements with conducting wires in the coil lead area.

An analytical study pointed out the fact that deterioration and premature failures of the platinum conductor wire was probably due to any or all of the items mentioned below:

a) Presence of moisture in the cable assembly after final fabrication and exposure to elevated temperatures causing free hydroxyl radicals and a non-oxidizing environment.

b) Impurities such as iron, etc., causing low melting point eutectics.

c) The presence of free silica from the silicon dioxide ceramic used in the insulator of the cable.

Two basic approaches to solve these problems were made. The first was to eliminate the reactions observed between the platinum conductor wires and the insulating ceramic and the second was to examine the possibility of utilizing another metal from the noble series for the conductor wires. Because of rhodium's excellent electrical characteristics, availability and potentially good chemical compatibility, this metal was chosen over several others.

The first approach to the incompatibility of the conductors with the ceramic insulator was to eliminate all possible traces of moisture from the ceramic prior to exposure of the cable assembly to elevated temperatures. Beads were made of the silica-magnesia material as shown in Figure 2. These were dried at various temperatures to drive out all moisture from the ceramic. The conductor wires were

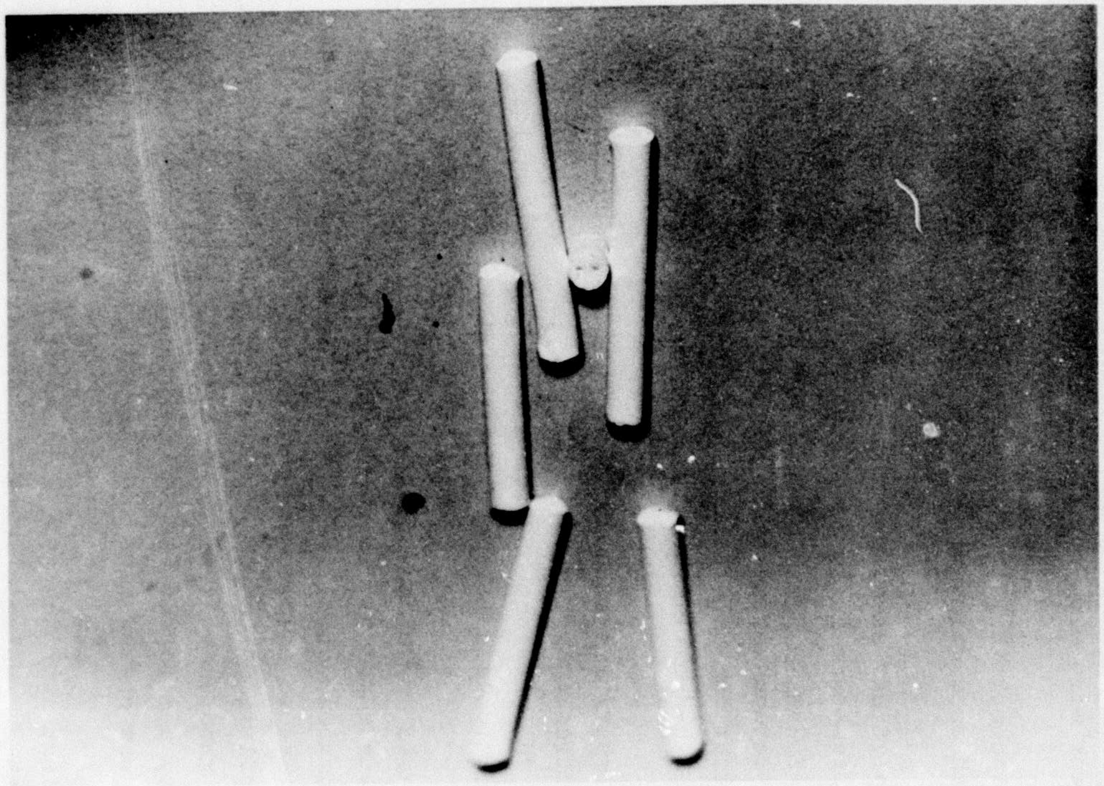


FIGURE 2. EXTRUDED SILICA - 2% MAGNESIA

then sheathed in these beads and placed in the Inconel tubing as shown in Figure 3 and subsequently drawn to the desired size. Radiographs were taken of the completed assemblies to ascertain the structural integrity and to insure that adequate separation existed between the two conductors. Electrical measurements of these completed assemblies were made to verify adequate insulation resistance and low capacitance.

This series of tests on the cable assembly proved several points.

1) No apparent problems existed between either of the conductor wires and the ceramic insulator after sufficient drying.

2) Because no failures were observed after removal of water from the ceramics no further tests were planned using other materials as insulators.

3) The cost of rhodium (approximately twice that of platinum) was offset by the fact that the electrical properties were improved by a large factor.

Samples that had been exposed for 25 hours to elevated temperatures in intimate contact with dried insulating material were examined microscopically for apparent degradation of the conductor wires. No substantial attack was apparent on these samples with the conductors retaining their virgin ductility.

The second problem appeared to be associated with the incompatibilities between the ceramic adhesive cements and the conducting wires in the coil leads. Evidence indicated that this problem was associated with high concentrations of phosphoric acid which was used in the fabrication of the ceramic as an inorganic binder. Phosphoric cement residuals remaining after drying can cause rapid deterioration of most

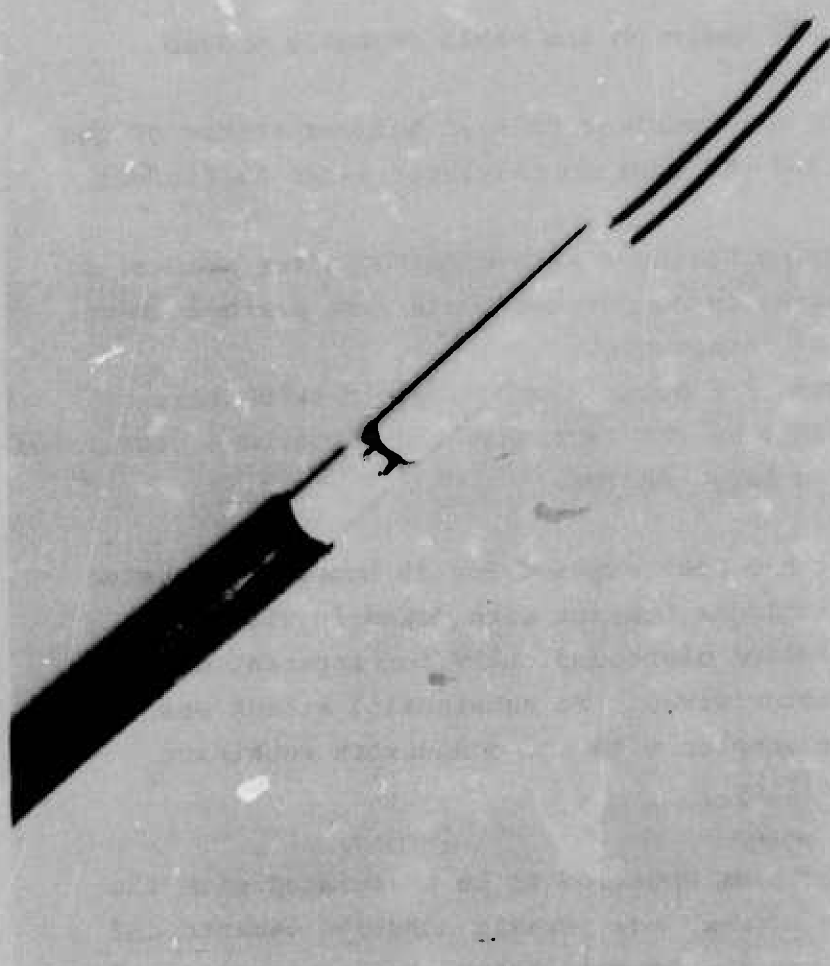


FIGURE 3. LOADING OF BEADS INTO SHEATH

metals at elevated temperatures. Several new cements were evaluated which did not use phosphoric acid as a binder with only three cements considered for serious testing. The remaining cements were temporarily set aside because of coarse consistency, lack of workability or rapid drying which would cause considerable fabrication problems. Those tested extensively were:

Saureisen #7 paste

Saureisen #78 paste

Cotronics #901

Test samples were fabricated and cured in the geometry shown in Figure 4. Electrical properties were measured at elevated temperatures, (932-2192°F) in the test fixture shown in Figure 5. The fixture was calibrated to eliminate the parallel resistance of the set-up and to provide only the resistance of the test specimen. The measured data are presented in Table 3. Because of the tendency of the Saureisen cements to glassify and attack the nickel test leads (nickel is a major constituent of the microphone deflection material) only the Cotronics 901 was tested further. Samples of solid ceramic, ceramic feed-thru, conductor, coil wire and ceramic cement were loaded into sealed nickel tubes with either no atmosphere (vacuum) or an inert atmosphere (helium) as shown in Figure 6.

Three main conclusions were drawn from this testing:

a) Cotronics 901 offers the best electrical properties and ease of fabrication.

b) The rhodium conductor wire appeared to be attacked more readily than the platinum wires for all ceramic cements evaluated.

c) The Secon E coated coil wires were deteriorated as much or slightly less than the ordinary rhodium conductors.

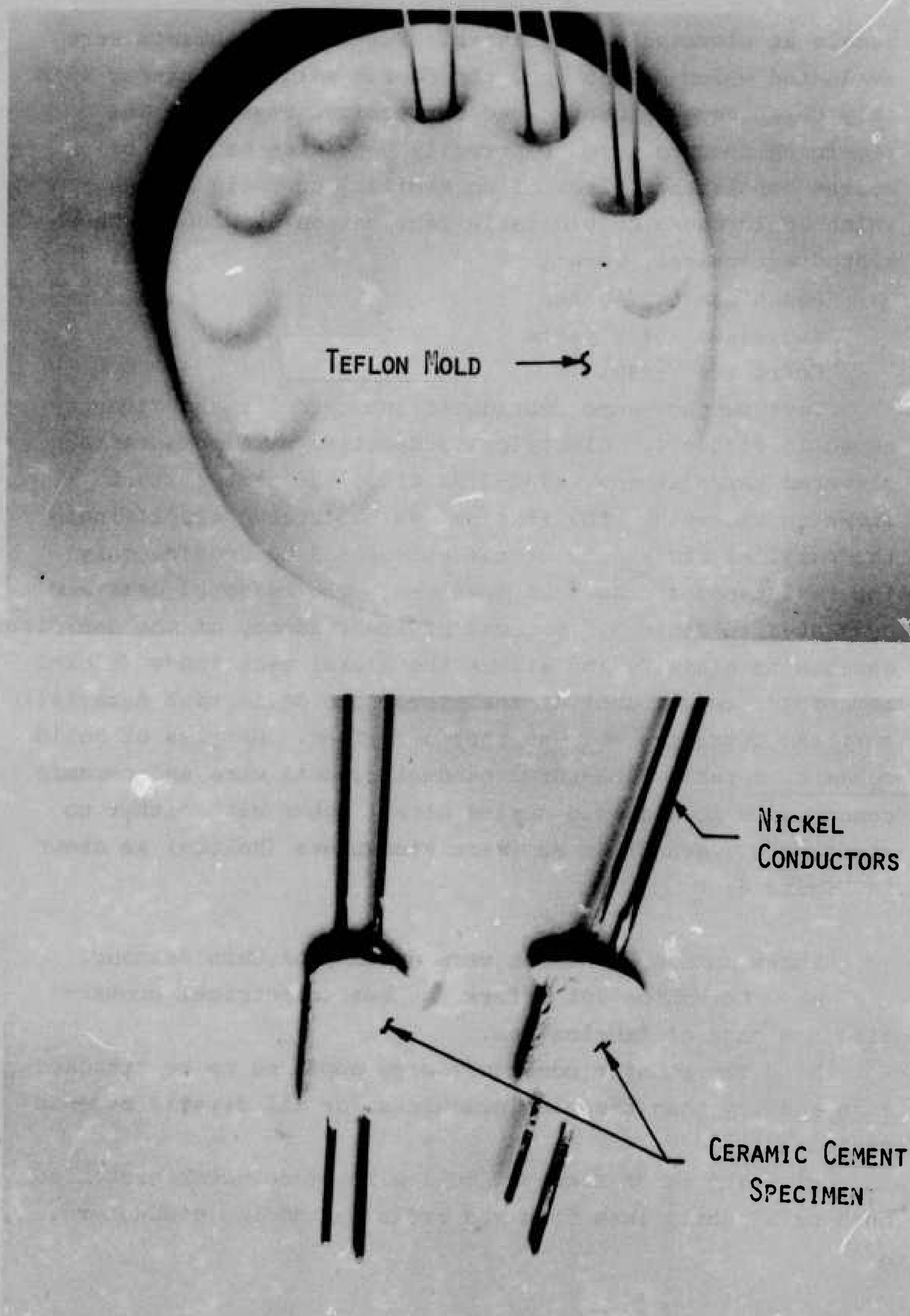


FIGURE 4. RESISTANCE TEST SPECIMENS

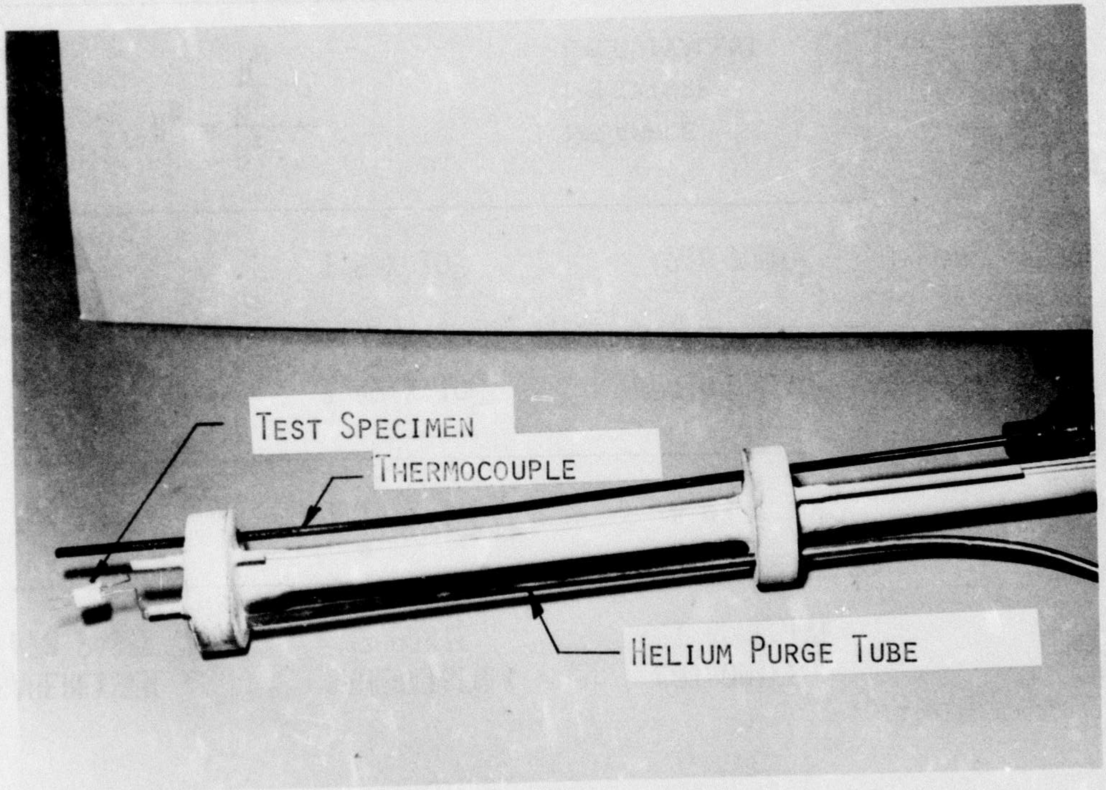
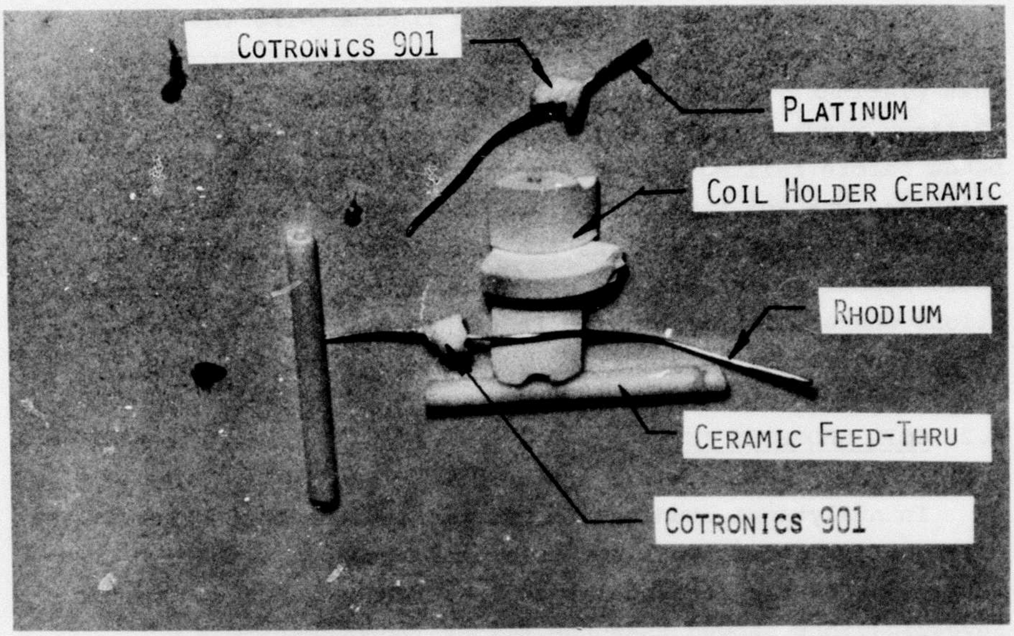


FIGURE 5. RESISTANCE TEST FIXTURE

TABLE 3. ADHESIVE RESISTANCE DATA

SAMPLE TEMP.	SAUEREISEN #78 PASTE	SAUEREISEN #7 PASTE	COTRONICS 901 ADHESIVE
1000°C	7×10^5	1.13×10^6	4.93×10^6
1100°C	---	3.42×10^5	1.09×10^6
1200°C	---	1.5×10^5	2.8×10^5
FORMULA FOR DETERMINING ACTUAL SAMPLE RESISTANCE	$R_S = \dfrac{R_F}{\frac{R_F}{R_E} - 1}$		S=SAMPLE F=FIXTURE E=EQUIVALENT



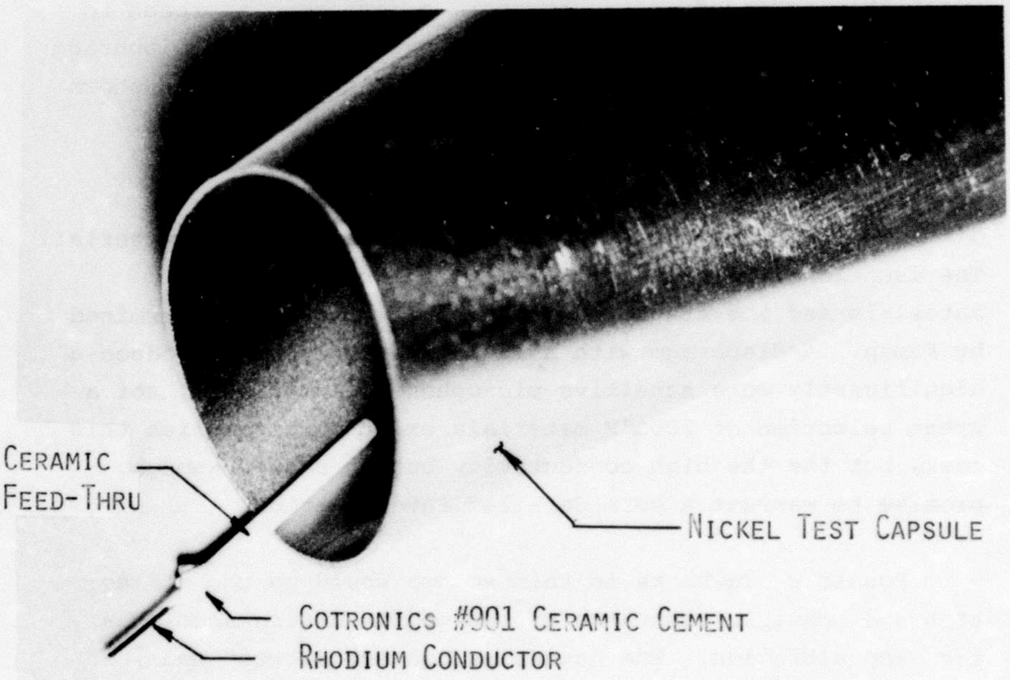


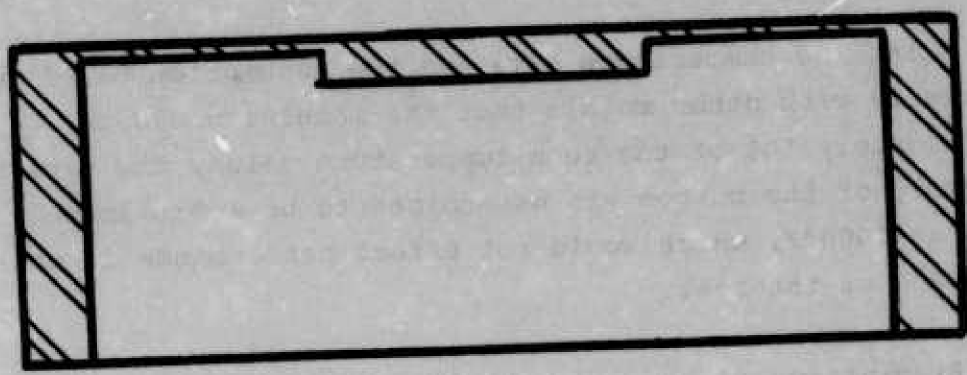
FIGURE 6. COMPATIBILITY TEST CONFIGURATION

A problem was noted while using rhodium wire in the coil lead areas. Although rhodium offers higher strength than platinum, it does so at a sacrifice of ductility. The platinum wires normally withstood approximately six 180° bends before failing whereas the rhodium wire can only withstand one 90° bend. This was observed in the "as received" condition as well as the fabricated condition. This would appear to inhibit the use of rhodium wires to configurations where multiple bending is required such as the coil extension lead wires.

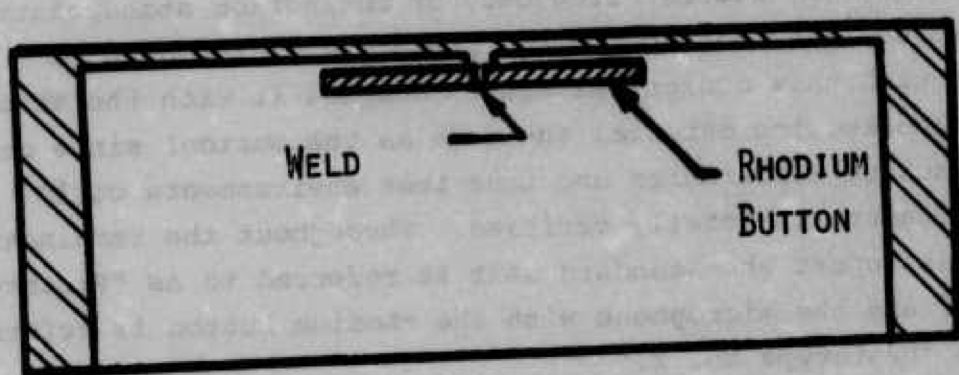
5.2 COIL GEOMETRY TESTS

In analytical studies, it was pointed out that other coil configurations were not practical but that slight variations of the rectangular coil would be examined. Further investigations showed that the slight improvement was not worth the increased cost; however, a different approach to improving the inductive coupling of the coil to the diaphragm was possible. With this scheme, part of the button as shown in Figure 7 is replaced by a high conductivity material. The sensitivity of the microphone is a function of the resistance of the cables and coils, the geometry of the diaphragms, and the resistivity (ρ) of the diaphragm material. The functional relationship between the resistivity of materials and the transducer sensitivity has been determined by Kaman. A diaphragm with a low resistivity will produce a significantly more sensitive microphone. Admittedly, not a great selection of 2000°F materials exist to accomplish this task, but the the high conductivity button showed enough promise to warrant a more detailed investigation.

Possible drawbacks to this scheme would be the deflection and possible resonance of the button during acceleration and vibration. The natural frequency (lowest mode) of a practical rhodium button was analytically determined.



STANDARD DIAPHRAGM



SPECIAL DIAPHRAGM

FIGURE 7. DIAPHRAGM CONFIGURATIONS

Although no modulus data exist for rhodium at 1093°C(2000°F), it was selected because of availability, oxidation resistance, and high modulus of elasticity at low temperatures.

Using low temperature data and the assumption based on experience with other metals that the modulus would be approximately 50% of the room temperature value, the natural frequency of the button was determined to be approximately 35Khz at 2000°F, which would not effect performance in the data band of interest.

Examination of the same rhodium button during acceleration showed that the deflection at the outer edge of the button during this loading was approximately 0.05% of the full scale deflection which also would not drastically effect performance.

Since this scheme does not have any significant drawbacks from the natural frequency or deflection standpoints, it was decided that one of the prototype microphones be built with this design feature to compare it with the standard unit (deflection material the same as the button) since only with active electronics and true test environments could this feature te totally verified. Throughout the remainder of this report the standard unit is referred to as "Prototype No. 1" and the microphone with the rhodium button is referred to as "Prototype No. 2."

5.3 SENSOR AND CABLE GEOMETRY TESTS

5.3.1 High Temperature Diaphragm Tests

A high temperature test fixture was designed and fabricated to examine the mechanical integrity of diaphragm materials. The fixture was fabricated from Inconel MA 753. It was designed to utilize a high temperature metallic seal fabricated from Haynes Research Alloy #8077. The pressure source provided up to ±11.78 psig at frequencies of up to 5 cycles per second.

The test objectives were to provide diaphragm design and performance data concerning maximum operating stress level, long term creep and distortion, and oxidation behavior. The materials tested were Haynes #8077 (Cabot Corporation), Inconel MA 753 (International Nickel Corporation), and DS Nickel (Sherritt Gordon Mines LTD). Material stock for the diaphragms was round bar for the DS Nickel and Inconel MA 753 with the diaphragm perpendicular to the extrusion direction. The material stock for the Haynes #8077 diaphragms was a 3/4 x 2 inch bar. Test diaphragms were made from the three mutually perpendicular directions designated as -1 (width), -2 (thickness) and -3 (length). The -1 and -2 specimens had the diaphragm parallel to the extrusion direction, which was supposedly the direction of highest strength. The -3 was in the same orientation that round bar would provide with the diaphragm perpendicular to the extrusion direction. The test diaphragm geometry is shown in Figure 8.

Standard test conditions for each specimen were as follows with the observed data presented in Table 4.

Test temperature - 2000°F
Test environment (one side) - air
Loading pressure - ±11.78 psig
Loading media (other side) - dry nitrogen
Loading frequency - approximately 2 cycles/sec

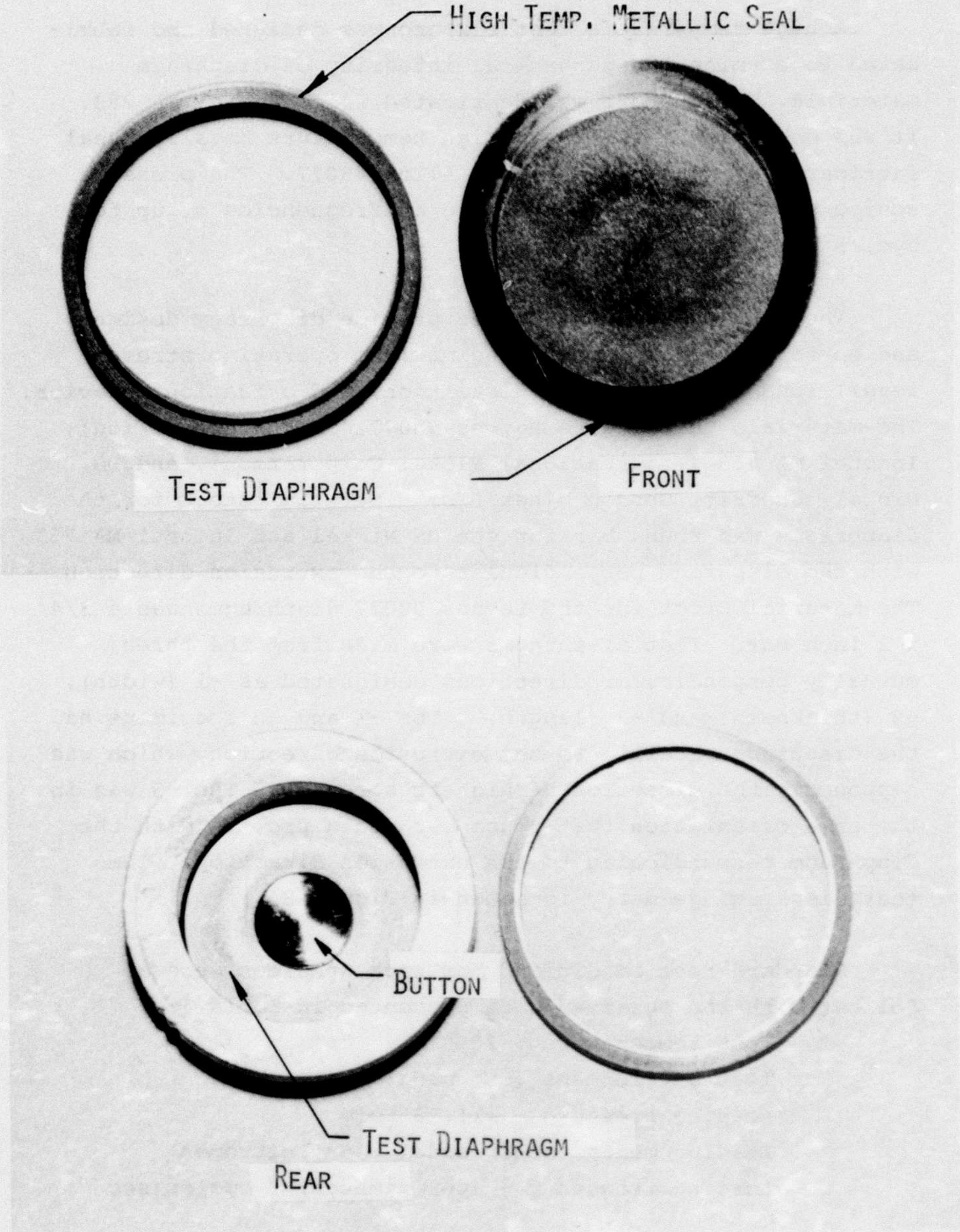


FIGURE 8. TEST DIAPHRAGM GEOMETRY

TABLE 4. DIAPHRAGM TEST DATA

Material	Test Stress (psi)	Total Cycles @2 cps	Oxidation (gms) + Gain - Loss	Distortion (inches max.)	Service Factor Distortion/Cycle/ Unit Stress
-1 Haynes #8077*	10,999	148,934	+.0074	.0023	---
-1 Haynes #8077	9,247	343,850	+.0019	.0004	0.125×10^{-12}
-2 Haynes #8077	11,232	183,000	+.0065	.0010	0.487×10^{-12}
-2 Haynes #8077	7,672	727,200	+.0076	.0051	0.408×10^{-12}
-3 Haynes #8077	11,673	174,033	+.0109	.0008	0.394×10^{-12}
-3 Haynes #8077	8,639	367,000	---	.0018	0.568×10^{-12}
Sherritt-Gordon DS Ni	11,783	187,010	-.0534	.0060	2.722×10^{-12}
Inconel MA-753	11,207	141,410	+.0092	.0017	1.073×10^{-12}
Inconel MA-753	8,742	360,850	+.0106	.0030	0.951×10^{-12}

* Solenoid valve failed in the open position allowing static pressure to be applied continuously.

From the test results, the following observations were made:

1) DS Nickel was not suitable for a diaphragm material because of the high oxidation rate.

2) A working stress of 11,000 psi was too high to achieve a useful life of over 100 hours @ 1093°C (2000°F) with any of the materials.

3) Haynes #8077 shows the best resistance to distortion and oxidation with Inconel MA 753 a close second.

4) A slight strength difference was evident between the various diaphragm orientations used with the Haynes #8077 alloy.

From this it was recommended that Haynes #8077 Research Alloy should be continued as the standard deflection material with Inconel MA 753 as an alternate.

5.3.2 High Temperature Spring

The design, location of material and testing of a high temperature wave spring was examined for possible cost savings and design simplicity. The major difficulties of incorporating such a spring into the microphone design are:

1) Selection of adequate material to operate at 2000°F in air.

2) Determination of the natural frequency of the spring mass system.

The design study was made to determine the thickness required to provide at least 100 g's of acceleration resistance at 2000°F. Although many materials having the required strength and oxidation resistance existed, only DS Nickel, (Sherritt Gordon Mines LTD) is fabricated in sheet stock. As was pointed out in the diaphragm testing, DS Nickel oxidizes quite rapidly and thus could only be considered as a spring material if there was assurance of a sealed environment inside the microphone. Wallace Barnes Division of Associated Spring in Bristol, Connecticut was selected for a future prototype build of the wave springs.

Since no DS Nickel wave springs were available to directly test the frequency response characteristics, a RENE-41 (General Electric material) wave spring was tested. The geometry of the available RENE-41 wave spring could be used in the geometry of the microphone so only material property values would need to be adjusted to make valid data comparisons. From an analytical study and an evaluation of the RENE-41 wave washer data, it was concluded that the wave spring planned for the 1093°C (2000°F) microphone would have a natural frequency at room temperature of at least 80 kilohertz and 55 kilohertz at 1093°C. The use of the wave spring would aid in design simplicity and overall cost of the microphone sensor.

5.3.3 Ceramic and Cable Insulation Shrinkage

To avoid the high temperature shrinkage of ceramics and cable insulation, tests were performed to examine this problem. A coil form was fired at 2192°F to stabilize the ceramic. Ordinarily the coil holder is treated with acid to harden the ceramic, but since the acid as well as the noted shrinkage at 2000°F was unacceptable, a new solution was sought.

The proposed solution was to fire a slightly oversized part at 1200°C (2192°F) which hardens the part adequately and shrinks it to the proper dimensions. Dimensional shrinkage noted in the test was established as the basis for making the part oversized.

To avoid shrinkage of the cable insulation, the beads were dried and dimensionally stabilized at 1204°C (2200°F).

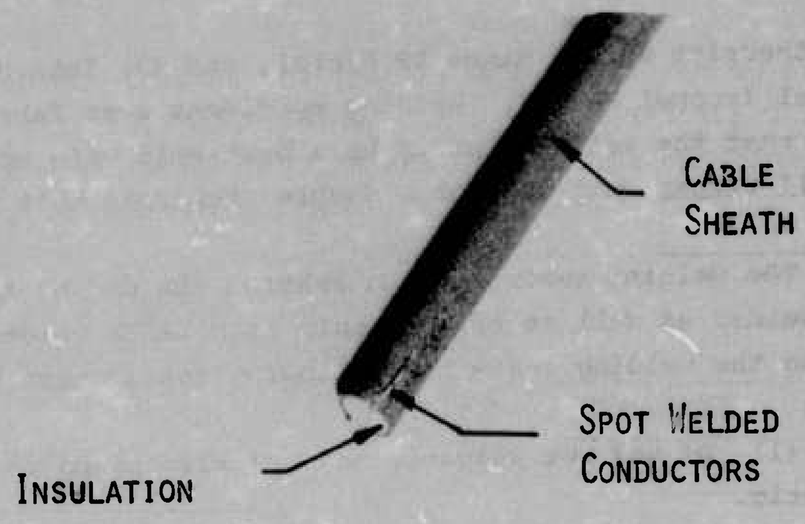
for a proper fit to the Inconel 600 sheath. Beads fired at 1204°C (2200°F) for one hour were the proper size for loading into the sheath. In the final drawing process the compaction of the silica - 2% MgO insulation was excellent allowing the proper finished diameter.

5.3.4 Differential Thermal Expansion of Cable Conductors and Sheath

To determine the effect of the differential thermal expansion between the conductors and the Inconel 600 sheath, tests were performed to simulate the actual geometry of the intended use. The geometry tested was a simulation of a cable with sheath and conductors fixed at one end and at 1093°C (2000°F). The remaining cable would have a decreasing temperature gradient to ambient (75°F) conditions at the other end. With this geometry, shown in Figures 9A and B, platinum and rhodium conductors were tested in fully drawn cable. Because of the brittle nature of the rhodium, (also observed with "as received" material), only the test shown in Figure 9B could be performed with rhodium. Results of these tests showed that for repeated tests going rapidly from room temperature to 2000°F to room temperature over 100 cycles, no failure of the conductors could be caused by thermal stretching. This fact also verified the extent to which removing the moisture from the cable insulation beads eliminated the imbrittlement of the platinum and hence rhodium lead wires. An analytical investigation also verified that both platinum and rhodium could survive the thermal differential stretching but that eventual failure could be caused by work hardening.

5.3.5 Welding Studies

Welding studies were performed on the three candidate deflection materials (1) Haynes Research Alloy 8077,



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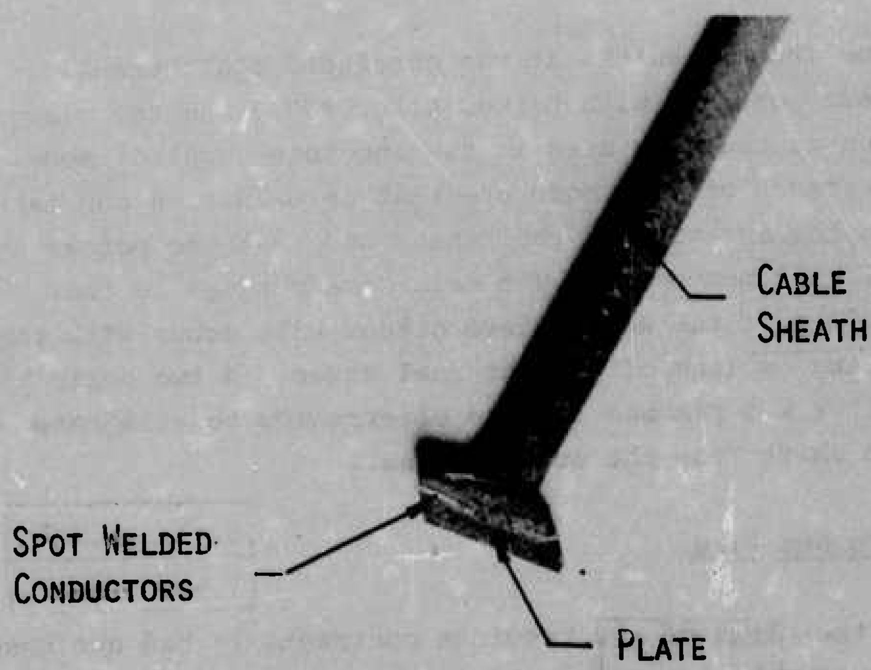

-B-

FIGURE 9. CABLE THERMAL EXPANSION TESTS

(2) Sherritt Gordon Mines DS Nickel, and (3) International Nickel Inconel MA 753. Welding specimens were fabricated such that the weldment could be a butt weld with no trepan, a half trepan butt weld or a double trepanned butt weld.

The welding tests were to examine the use of the pulsed TIG welder as well as the commonly used LASER welder. During the welding tests the following conclusions were made:

(1) DS was not weldable and was also found to be magnetic.

(2) Inconel MA 753 was weldable with great difficulty requiring welding with both the LASER and pulse TIG welders.

(3) Haynes Alloy #8077 was LASER weldable after careful cleaning with hydrochloric acid. No "hot-cracking" of the weld zones was noted after this cleaning procedure was used.

From these results, it was concluded that hermetic welds were possible with Haynes Alloy #8077 and the microphone sensor could be used in the absolute (sealed) mode. The advantages of this mode are that no oxidation can take place on the interior of the sensor and that the porous vent filter is not necessary. The main disadvantage is that large shifts of the sensor zero output will occur with the heating and cooling of the internal gases. A two hertz high pass filter was planned for the electronics to eliminate the zero shift from the output signal.

5.3.6 Porous Plug

At the close of the previous contract, it had not been possible to make hermetic welds on the transducer, so vents were provided to make the microphone operate in the "gage" mode. The vents for the previous prototype microphone were deemed inadequate because rather large foreign particles could enter the transducer and prevent proper operation. A porous filter plug was designed to prevent entry of these foreign objects, yet not affect frequency response. A vendor was selected as a supplier for platinum porous filter plugs should this option be selected.

5.6 ELECTRONICS TESTING

5.6.1 Performance of Electronics

The electronics design was to be based on the recently developed Kaman KP-1910 series, so an evaluation of the noise of that electronics was made. The greatest contributor of noise in the KP-1910 electronics was determined to be the AC amplifier stage, an operational amplifier. Replacement of this unit was the main effort of the electronics improvement. Several integrated circuit amplifiers were evaluated.

To provide an adequate temperature coefficient, a high frequency operational amplifier was selected because of its high degree of gain stability. It was essentially equal to the stability of the feedback resistors. The outstanding feature of this device is that it has about 60 dB of open loop gain at 1 MHz compared to about 40 dB of the next best devices. This feature will allow sufficient feedback to insure a high degree of stability with temperature as well as ground loop rejection.

It was also noted that the voltage gain of the AC amplifier in the KP-1910 electronics was to be increased in order to improve the signal to noise ratio. The gain has been increased 5 dB. The full scale output voltage was established at 2.5 volts DC corresponding to a pressure of 25 inches of mercury. Since the dynamic range of the output of the electronics is from -9 to +10 volts, a DC zero shift with temperature of almost three times the full scale output (due to thermal zero shift of the sensor) could be accommodated.

5.6.2 Analysis of Noise Measurements

Noise measurements were performed using two different methods. The first method used a Hewlett Packard spectrum analyzer consisting of a 141T display section, 8552B Intermediate Frequency sectic and 8556A low frequency tuning section. All measurements using this method were made at room temperature and at zero pressure. The 0 dB reference level for all measurements was taken to be 2.5 Vdc. The total noise rejection measured over a 10 KHz bandwidth was -86.3 dB. Over a 100 Hz bandwidth, the noise level was measured as approximately -106 dB, which calculates to be -84.3 dB over a 10 KHz bandwidth, only the 2 dB difference between the calculation and measurement.

The second method for measuring the output noise level was to use an average responding AC voltmeter, a Hewlett Packard Type 400 GL. This meter contains a 100 KHz low pass filter. In all of the measurements this filter was used to eliminate the possibility of including any remaining 1 MHz carrier signal passed through as part of the random noise.

The noise measurements shown in Table 5 were taken using this second method. This table shows the effects of electronics temperature and of a full scale sensor output upon the noise level. The effects of temperatures lower than room temperature were not measured because the breadboard was not constructed with components specified for low temperature operation. The prototypes were planned for construction using components specified for the military temperature range.

At 24°C(75°F), Table 5 indicates a noise level of -86.7 dB at zero pressure. At full scale pressure this is increased to -82.2 dB, an increase of about 4.5 dB. This increase is due to the fact that noise from the oscillator

TABLE 5. ELECTRONICS OUTPUT VS TEMPERATURE

OUTPUT	PRESSURE	24°C	50°C	76°C
DC mV	Zero	-2	+6	+28
DC mV	Full Scale	2503	2518	2558
Noise mVrms	Zero	0.115	0.120	0.125
Noise dB*	Zero	-86.7	-86.4	-86.0
Noise mVrms	Full Scale	0.195	0.195	0.200
Noise dB*	Full Scale	-82.2	-82.2	-81.9

*dB calculations are with respect to 2.5 Vdc is fed through with the oscillator signal when the bridge is unbalanced by the application of pressure to the sensor which can be minimized by decreasing open loop gain. The worst case noise level occurs at 76°C (169°F) and full scale pressure. The voltmeter measurement indicates a noise level of -81.9 dB at this point.

Large thermal zero shifts of the sensor were also a concern. A large shift could cause an imbalance of the bridge which would affect the noise level in the same manner as does a bridge imbalance caused by pressure.

5.6.3 Design of AC or DC Switchable Output

In order to provide a system output which was not affected by the thermal zero shift of the sensor, it was recommended that a high pass filter be incorporated to eliminate the DC component of the output signal. A switch would be located on the electronics to switch this filter in or out. The output filter would also be modified to provide a one hertz high pass lower corner frequency and a 10 kilohertz low pass upper corner frequency. Component tolerances would be selected such that a lower cut-off frequency of at least 1.5 hertz would be assured.

6.0 MICROPHONE SYSTEM DESIGN AND FABRICATION

6.1 SENSOR

The microphone sensor design was patterned after the KP-1910 high temperature pressure transducer presently in production at Kaman. The KP-1910 transducer system was engineered for ease of fabrication and assembly and a design similarity would allow the 1093°C(2000°F) microphone system to take advantage of the production and assembly tooling and fixtures. Details of the design are shown in Figure 10. Design features included:

(1) 0.006 inch thick diaphragm with -1 direction (see Section 5.3.1) Haynes Alloy #8077 deflection material.

(2) Prototype 1 was fabricated with the standard button indicated in Figure 7. Prototype 2 was fabricated with the high sensitivity rhodium button noted in the same figure.

(3) 100 turn coils of rectangular cross section fabricated with 0.002 inch diameter rhodium wire and coated with 0.0075 inch thickness of Secon "E" insulation.

(4) 0.010 inch diameter platinum - 13% rhodium lead wires.

(5) Haynes Alloy #8077 high temperature thrust spring.

(6) Alumina coil holder and feed-thru ceramics.

(7) Cotronic #901 ceramic cement for use in the coil and around the feed-thru ceramic.

(8) Haynes Alloy #8077, alumina and platinum tube ceramic-to-metal seal vacuum brazed using Paloro* braze material.

(9) Metallic sheathed high temperature instrumentation cable with 0.125 inch outside diameter by 0.012 inch wall thickness Inconel 600 sheath, 98% silica-2% magnesia predried insulation beads and 0.010 inch diameter platinum-13% rhodium conductors.

(10) Standard Kaman miniature metallic sheathed cable connector.

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* Trademark of the Western Gold and Platinum Co. for a 92% gold-8% paladium braze material.

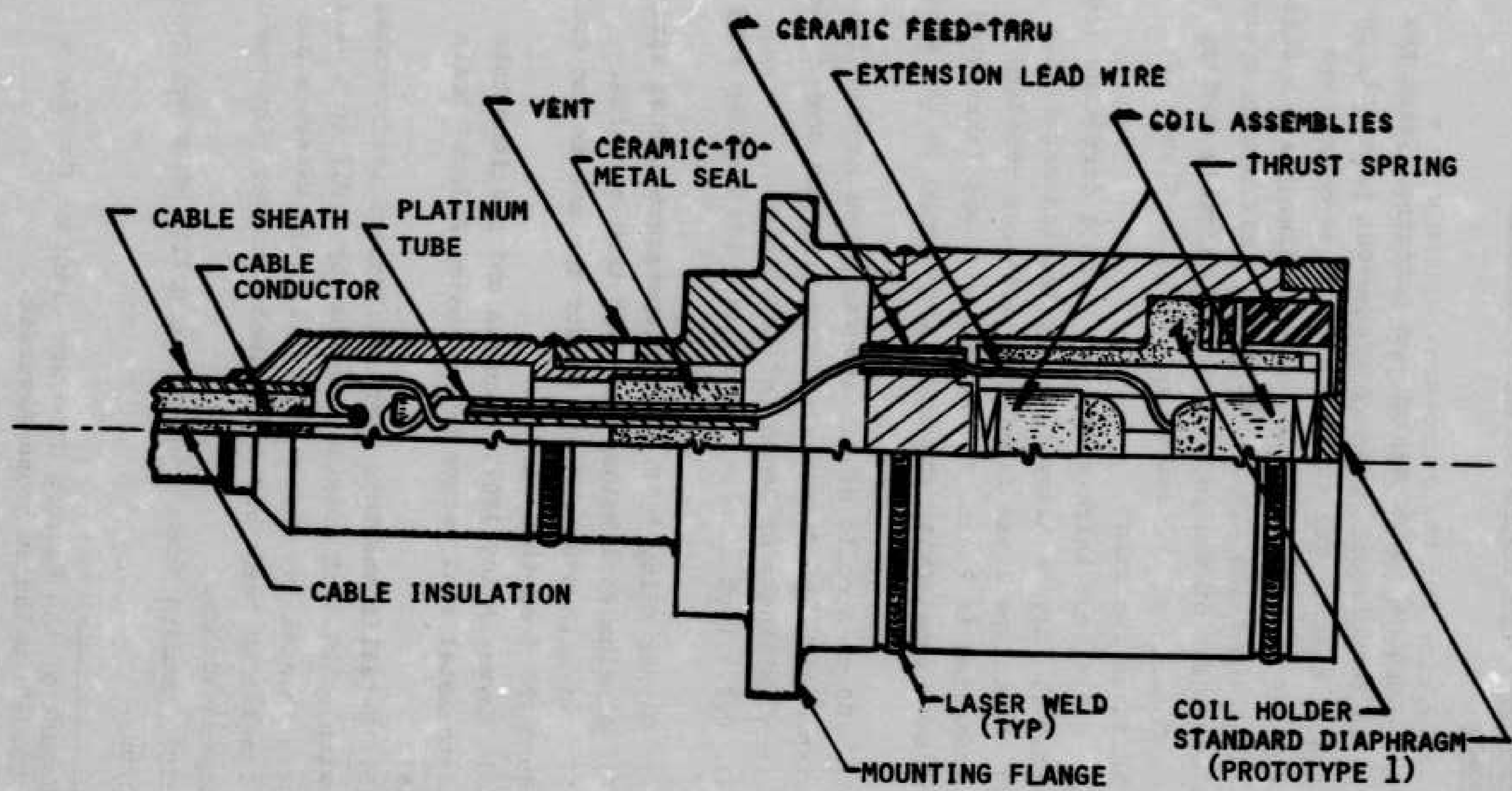


FIGURE 10. MICROPHONE DESIGN DETAILS

6.2 ELECTRONICS

The electronics for the microphone system were a special low noise version of the KP-1910 electronics. The special low noise components were added to provide a system signal-to-noise ratio greater than 80 dB. The design improvements added to the basic KP-1910 features outlined in Section 4.4 are (1) low noise design utilizing military specification components for the AC amplifier, demodulator and output amplifier stages of the electronics and (2) an AC or DC switchable output with an AC data band from 1 hertz to 10 kilohertz.

6.3 DESIGN PROBLEMS

At the conclusion of the experimental studies, it was decided to put the microphone sensor in the "absolute" or sealed mode. The first prototype assembly was back-filled with helium in such a manner that it could operate from sea level to exo-atmosphere altitudes at 1093°C(2000°F) without internal gas expansion exceeding the allowable diaphragm stress. The zero output voltage associated with this temperature and pressure change was larger than expected. Compensation in the electronics was not practical so a small vent hole as shown in Figure 10 was added. With the addition of the vent hole, no loss in microphone performance was experienced since only static pressure measurements would no longer be possible. With this vent, oxygen would be permitted in the interior of the sensor. Since DS Nickel was observed to oxidize so rapidly, the planned use of the wave spring was abandoned and a thrust spring made from the highly oxidation resistant Haynes Alloy 8077 was used.

After preliminary operation for electronics adjustments, failures of the rhodium cable conductors and platinum extension lead wires were noted. The platinum extension lead wires were studied to determine the cause. It was noted that the platinum tensile strength had been reduced by greater than a factor of five. Further tensile testing of candidate materials indicated that the platinum-13% rhodium wire had better ductility than the platinum wire and was only slightly affected by exposure to an inert atmosphere in the presence of microphone materials.

Failure of the rhodium conductors in the high temperature cable was also investigated. Rhodium by its nature is quite brittle but sections of rhodium from the failed cable shown in Figure 11 were tested only to find it unaffected by the exposure to the 1093°C(2000°F) environment. Since no bending was used as a part of the experimental differential thermal expansion tests described in Section 5.3.4, a test including bending was performed. The test included heating the original cable used for Section 5.3.4 results to 1093°C, removing it from the furnace and bending slightly while hot. This procedure duplicated the actual use situation since the high temperature cables would always bend under the loading of extension cable weight. Within four such cycles, the rhodium conductors had failed. The conclusion from these tests were that the combined differential thermal expansion strain and the bending strain had exceeded the elongation capability of the rhodium and a more ductile material was necessary. Because of the tests described earlier, the platinum-13% rhodium was again chosen.

The foregoing solutions were felt to be adequate but not optimum, so a basic study of the cable problems was made. This study examined all aspects of the lead wire failures in both contracts F33615-72-C-1199 and F33615-74-C-3011. Considered in the study were the ceramic cements, the insulations, the ceramics, the lead wire materials and the environment. The technical literature as well as thermocouple sales literature indicated the following:

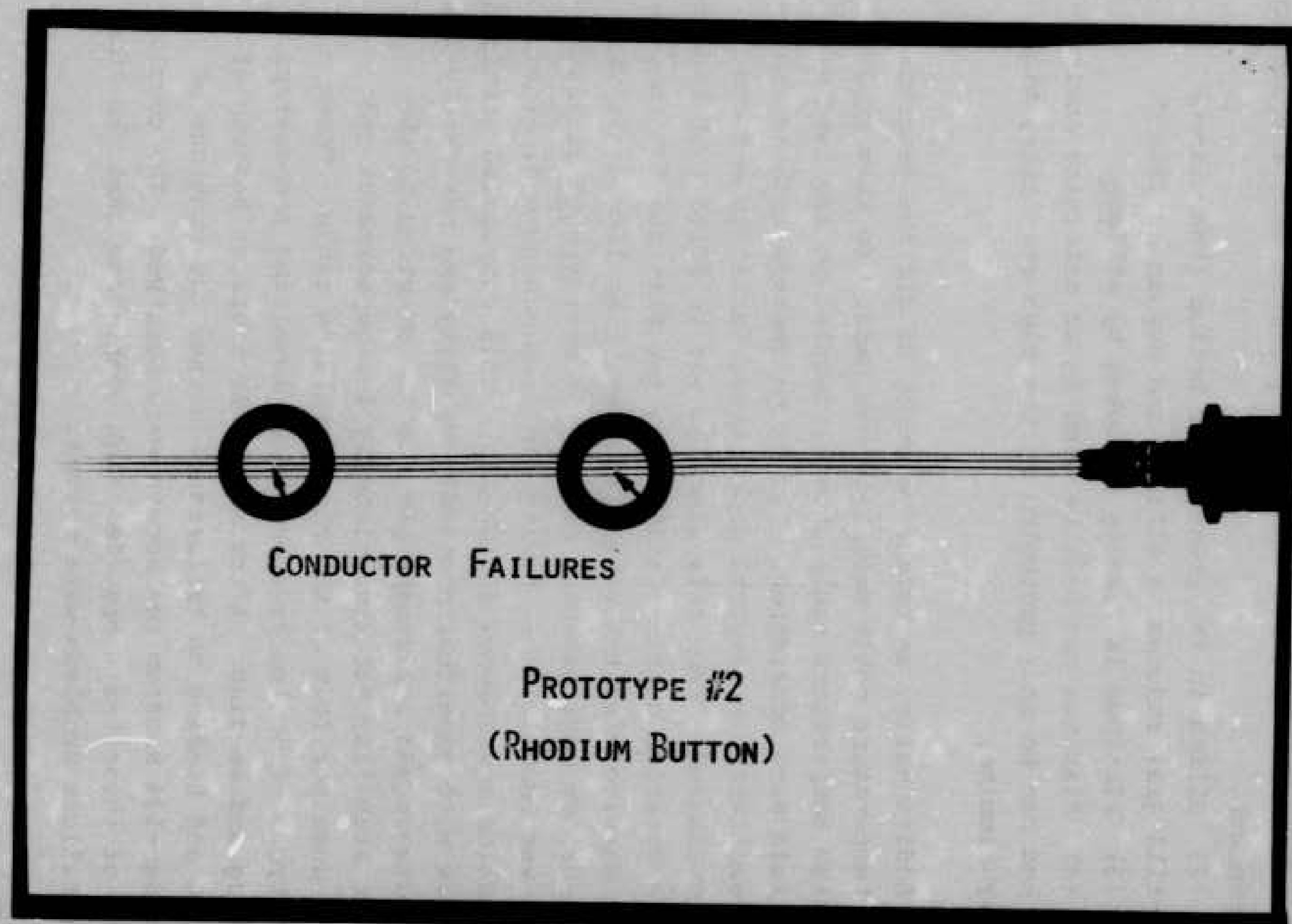


FIGURE 11. CABLE CONDUCTOR FAILURES

(1) Platinum should not be used in any reducing environment. A vacuum or inert atmosphere presents such a reducing environment.

(2) Silica in the presence of helium (the planned back-fill gas) reduces to silicon and oxygen at 1300°C.

(3) Platinum is readily attacked by silicon.

(4) Platinum can best be used in an oxidizing environment and can be only protected by the high stability, high purity alumina.

Additionally, an extensive study of all the possible high temperature cable materials was made. In this study all high temperature cable sheath, insulation and lead wire materials were considered. Design parameters such as chemical reactivity, electrical properties, ductility and cost were evaluated. From this study it was verified that because of the superior chemical stability, the platinum-13% rhodium could survive with the silica insulation as long as it was in an oxygen environment. Also, the most practical 1093°C cable was identified as having platinum conductors, alumina insulation and Inconel 600 sheath. This compromise provided a cable with excellent chemical stability and moderately low capacitance and resistance per foot as compared to the lesser stability but exceptionally low capacitance and resistance per foot of the rhodium-silica cable. Tests of both types of cables have been made involving temperature cycling and bending. After nearly 50 hours of heating at 1093°C and bending no failures of either the platinum or platinum-13% Rhodium conductors were observed. The conclusions of these tests provided high confidence that the lead wire failure problems were solved.

7.0 MICROPHONE TESTING

The experimental data gathered during the testing of prototype 1 (standard diaphragm) and prototype 2 (rhodium button) diaphragm are presented in detail in the following sections and in a tabular summary at the end of this section (Table 6).

7.1 SENSITIVITY

The sensitivity calibrations of prototypes 1 and 2 are shown in Figure 12 for 70°F, Figure 13 for 1000°F, Figure 14 for 1500°F, and Figure 15 for 2000°F. The composite of these four figures is in Figure 16 which shows the temperature dependence of the calibrations. Data to 130 dB were generated with an artificial voice, data from 170-187 dB were generated by static calibration, and the 191 dB data were generated by the quasi-static (low frequency) square wave generator. Artificial voice data were obtained to as low as 90 dB for prototype 1 and 70 dB for prototype 2.

The straight lines of these semi-log plots indicate that the log of the output signal is proportional to the sound pressure level in dB. The proportionality constant can thus be defined as a sensitivity in decades of output signal per dB. These sensitivites are tabulated below with the appropriate percentage of deviation from the average of the sensitivities at the four test temperatures. The more traditional microphone sensitivity level is also listed. The sensitivity level gives the system sensitivity in dB below 1 volt per microbar (1 microbar = 1 dyne per square centimeter).

Temp. in Degrees F	Sensitivity Level dB re 1 V per microbar	Sensitivity decades/dB	% Sensitivity Deviations from average
	Prototype 1		
70	-114.42	0.0513	+2.15%
1000	-117.94	0.0482	-4.00%
1500	-120.15	0.0494	-1.63%
2000	-118.05	0.0520	+3.48%
Average	-117.64	0.0502	
	Prototype 2		
70	-103.54	0.0506	+1.87%
1000	-109.35	0.0488	-1.85%
1500	-113.08	0.0491	-1.25%
2000	-105.07	0.0503	+1.23%
Average	-107.76	0.0497	

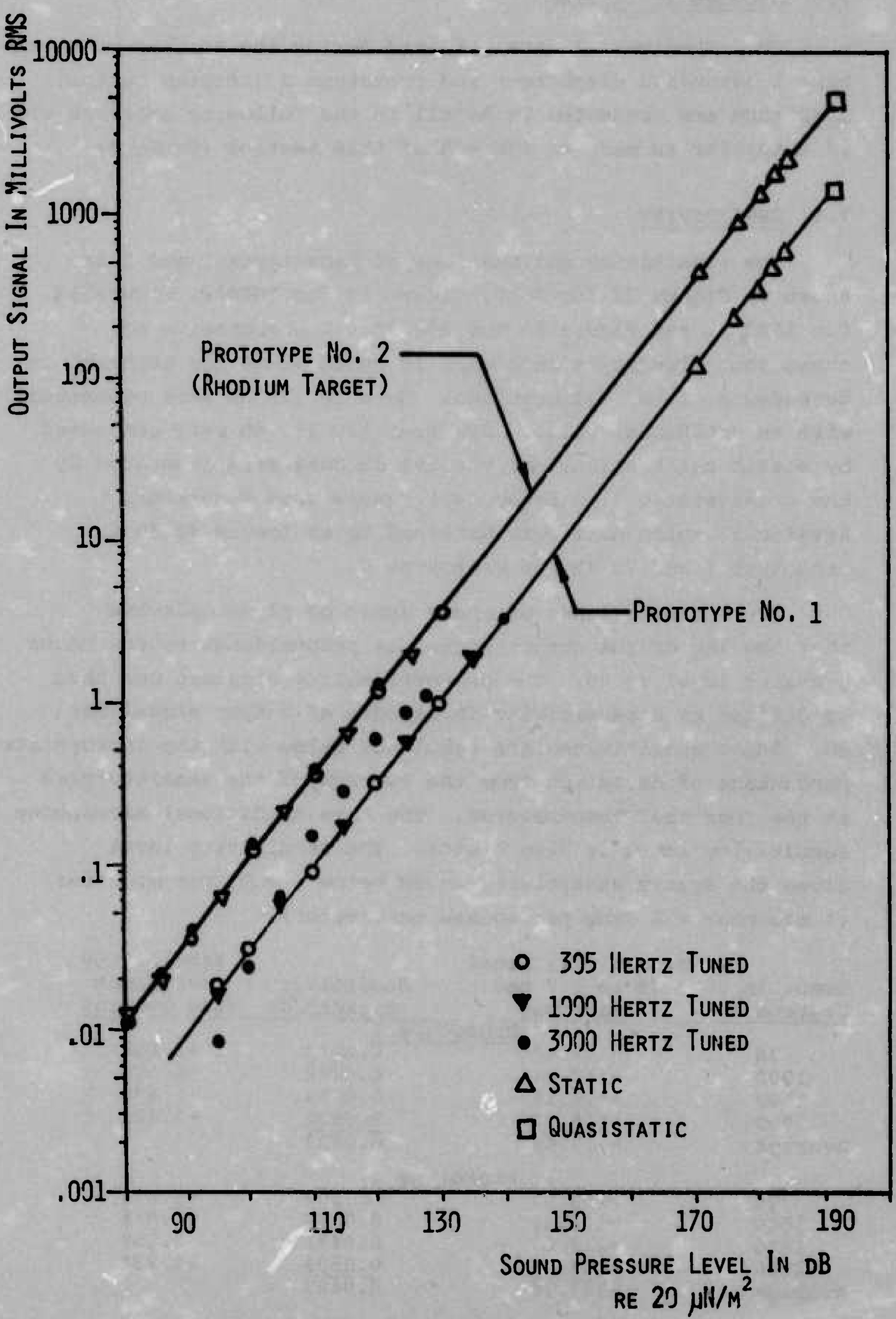


FIGURE 12. SENSITIVITY AT 70°F

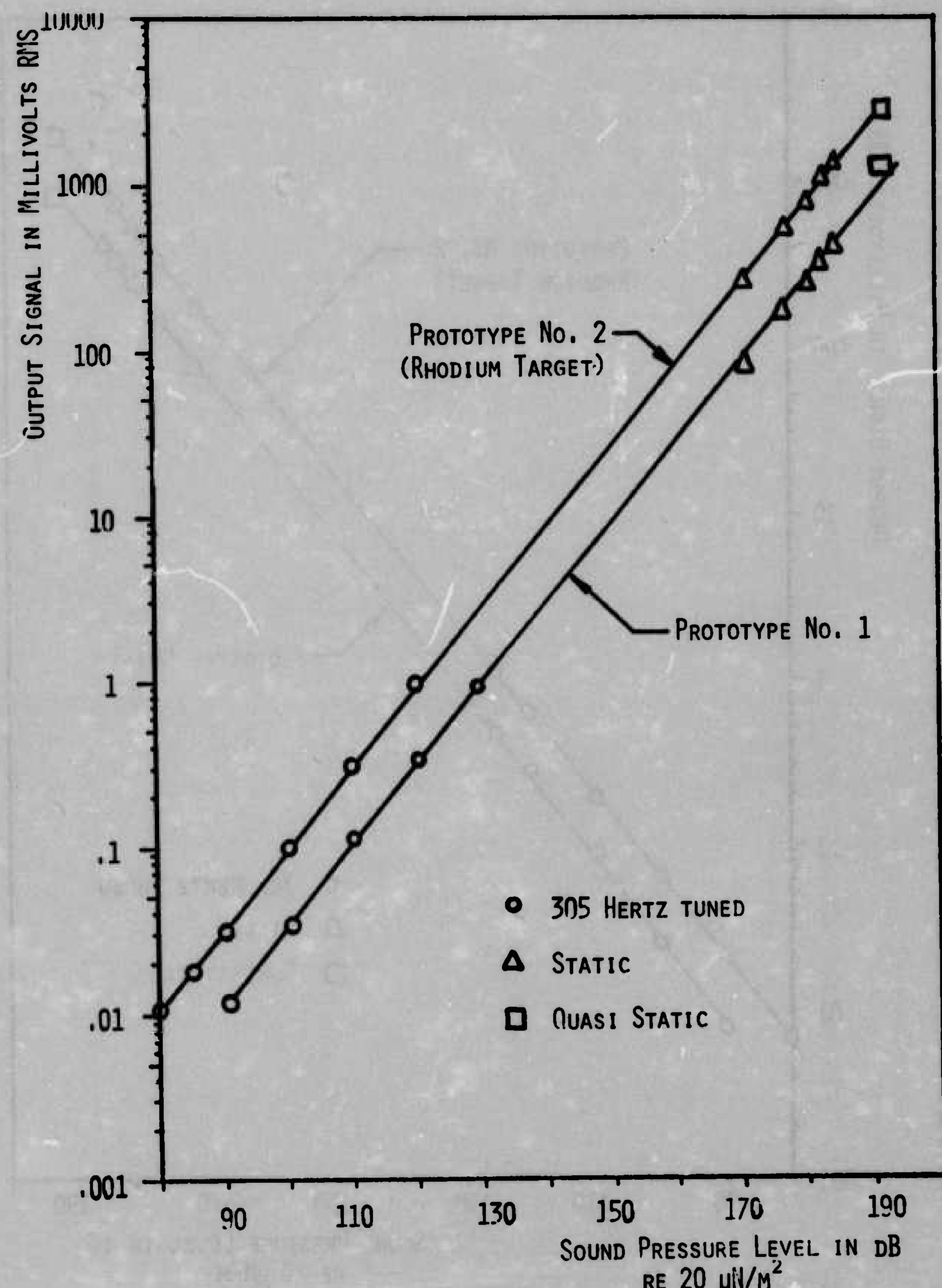


FIGURE 13. SENSITIVITY AT 1000°F

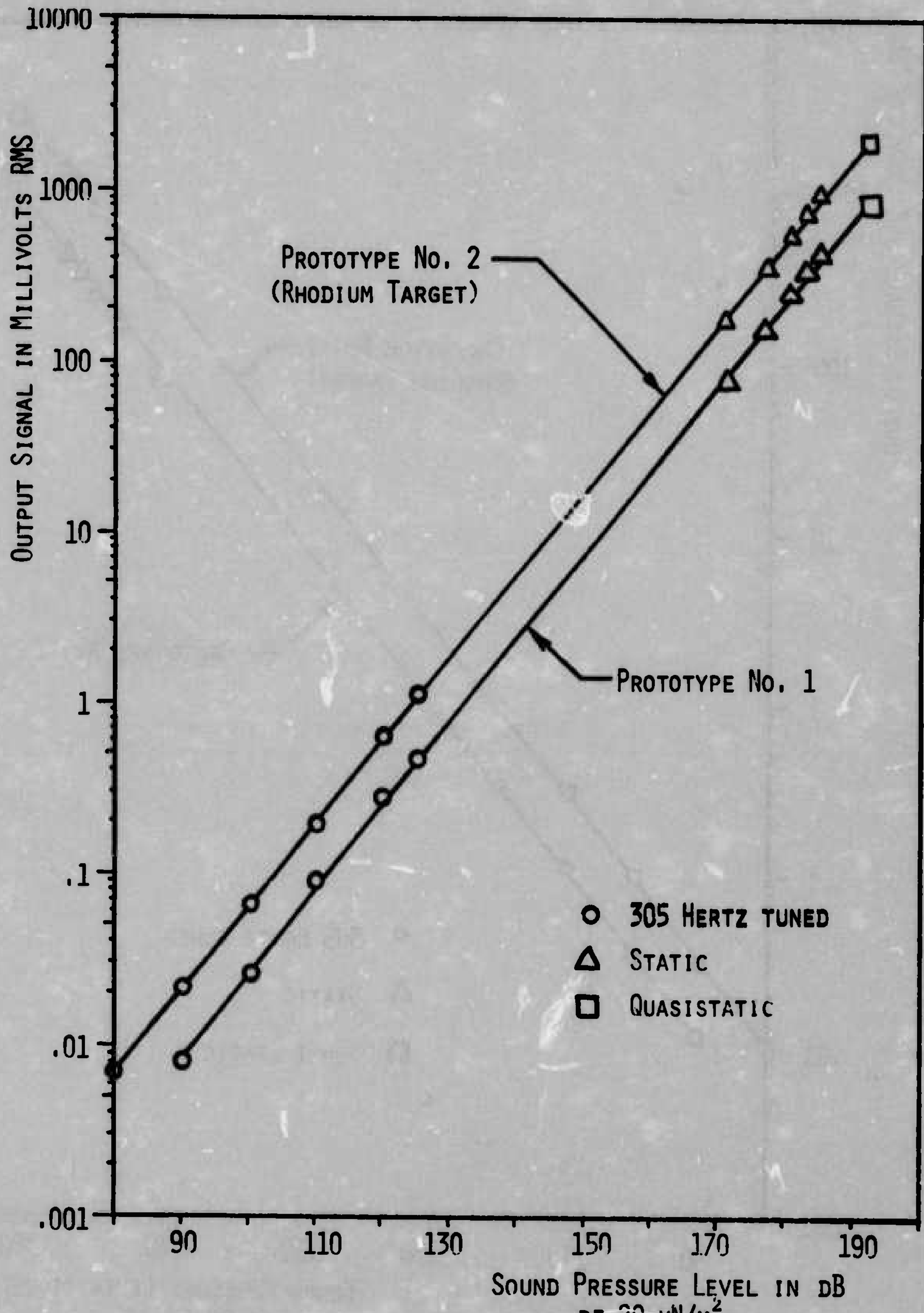


FIGURE 14. SENSITIVITY AT 1500°F

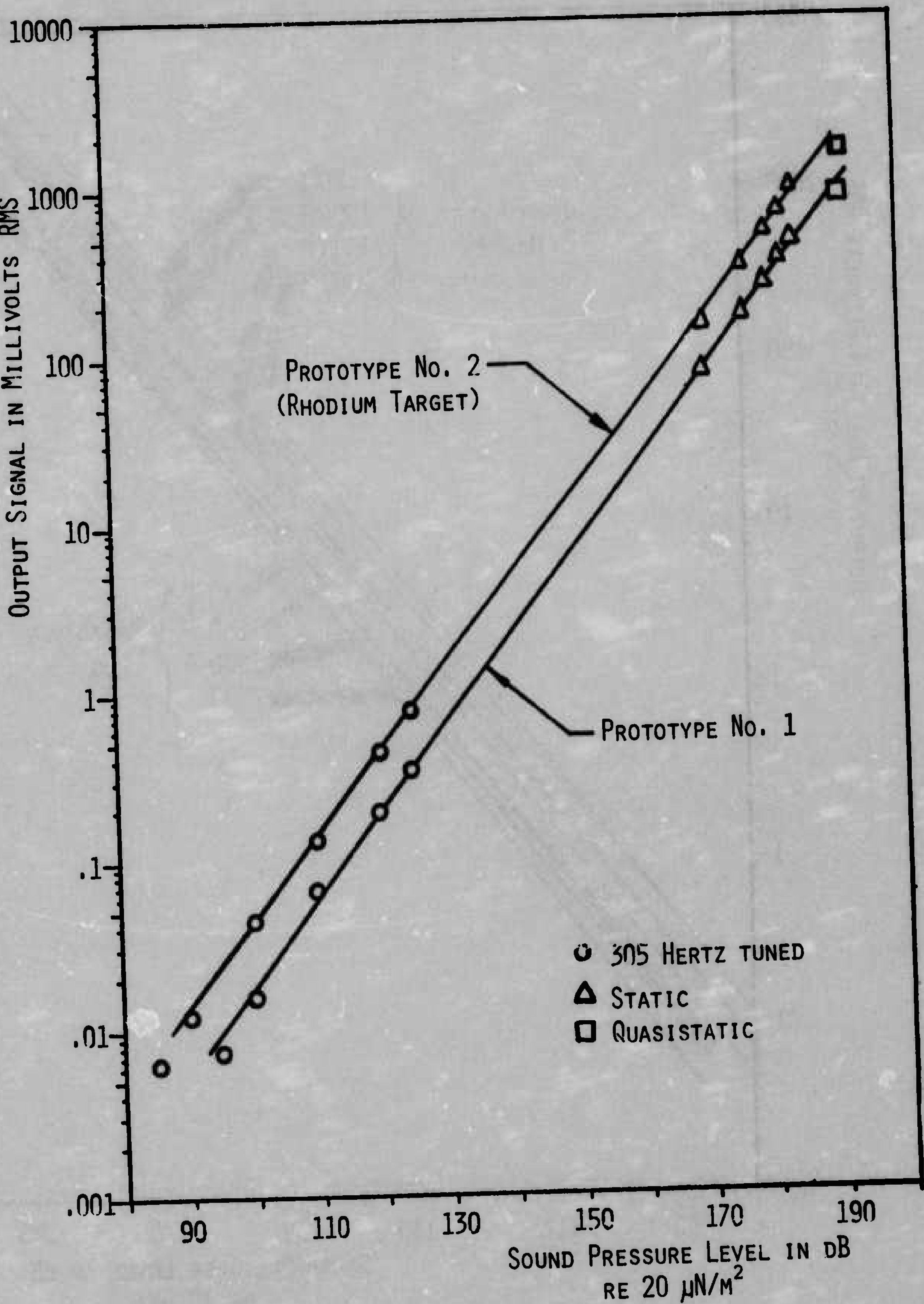


FIGURE 15. SENSITIVITY AT 2000°F

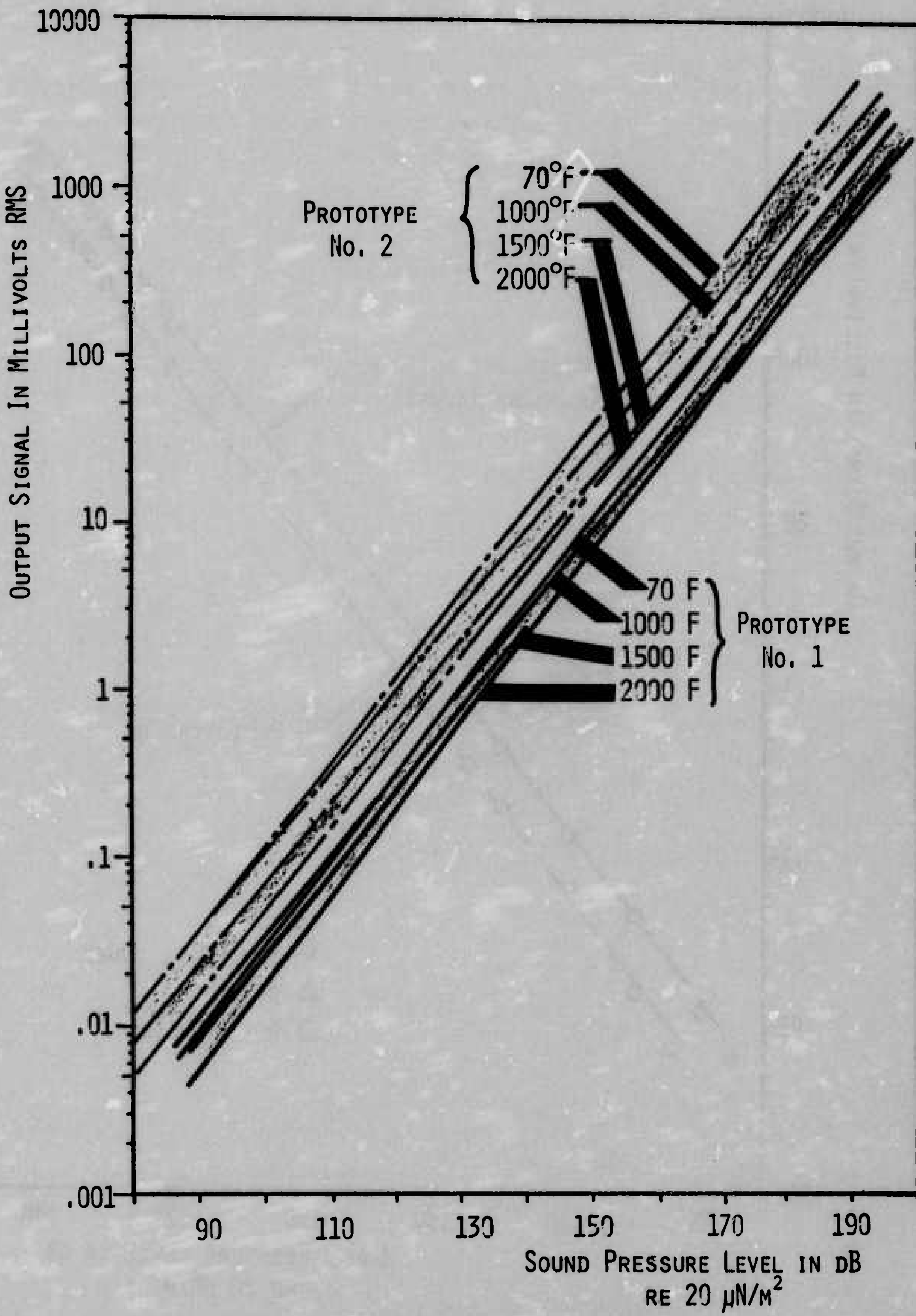


FIGURE 16. SENSITIVITY VERSUS TEMPERATURE

The largest coefficient of thermal sensitivity shift for prototype 1 is between 1500°F and 2000°F and this coefficient is a very tolerable 0.01%/°F. The comparable coefficient for prototype 2 is also between 1500°F and 2000°F and is 0.005%/°F, half the prototype 1 value.

The design goal no. 1 given in section 2.0 is ±0.5% from -65° to 2000°F. This very tight design goal was not met but the values listed above represent performance that is normally not obtainable by any room temperature measuring instrument of any operating principle. Thus, this performance over the 2000°F range is considered very acceptable.

The basic sensitivities shown in the figures indicate that prototype 2 has the predicted higher values. The prediction was 6 dB gain and this is very close to the values measured.

7.2 DYNAMIC RANGE

Figures 12 through 16 show that measurements were made within a dynamic range that exceeded 100 dB, actual measurements with a tuned microvoltmeter were made at 90 dB for prototype 1 and at 70 dB for prototype 2. The design goal of 100 dB was thus met and exceeded with both prototypes.

7.3 OUTPUT LINEARITY

The output linearity was measured as static pressure versus voltage output. Pressures were applied from 0 to 10 inches of mercury (gage) at four temperatures, 70°, 1000°, 1500°, and 2000°F. Both prototypes were tested and the deviations from linearity are shown in Figures 17 and 18 and the deviations are calculated as a percentage of full scale being the maximum test pressure of 10 inches of mercury. This represents linearity in the direction of positive pressure only.

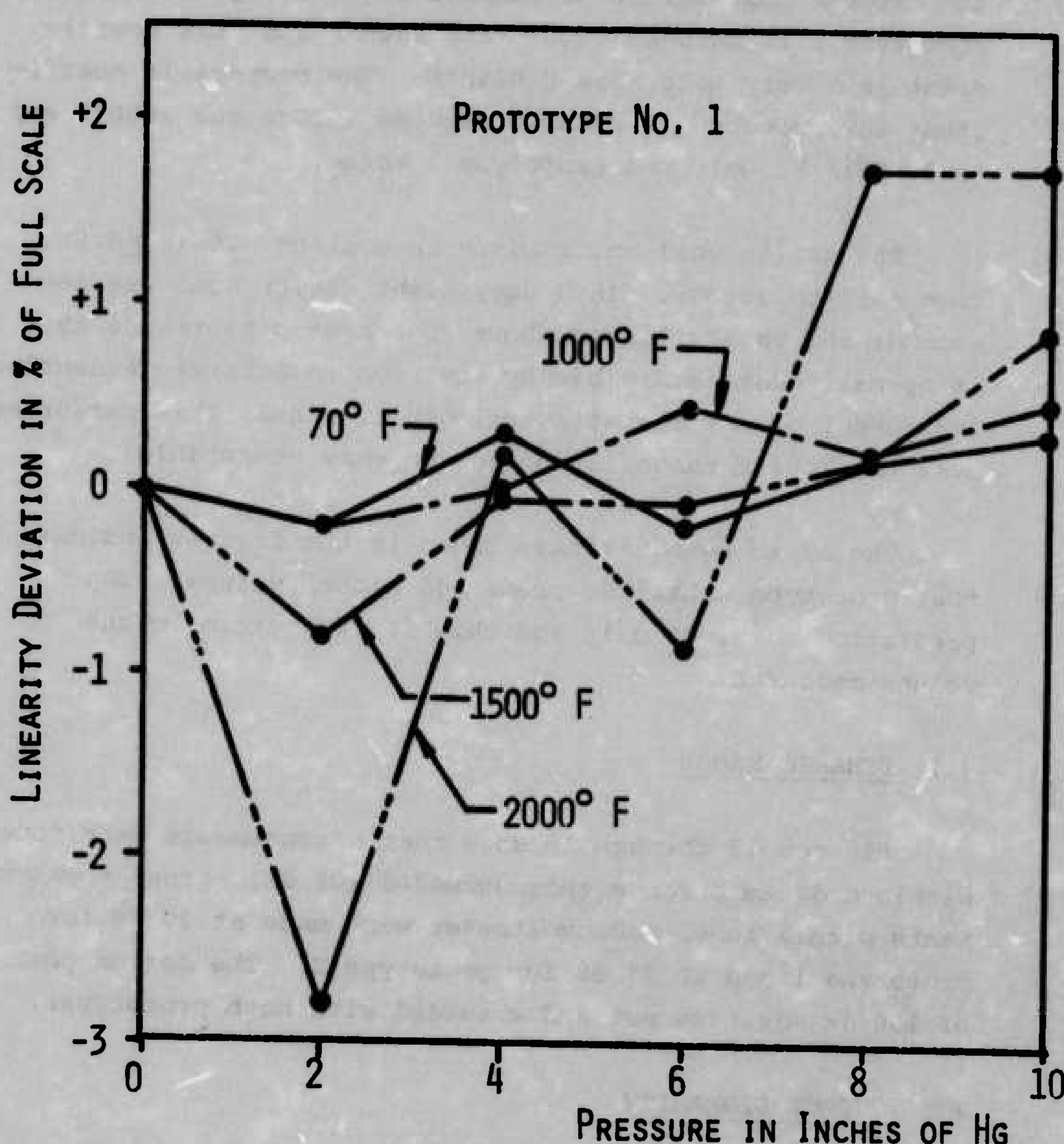


FIGURE 17. PRESSURE LINEARITY

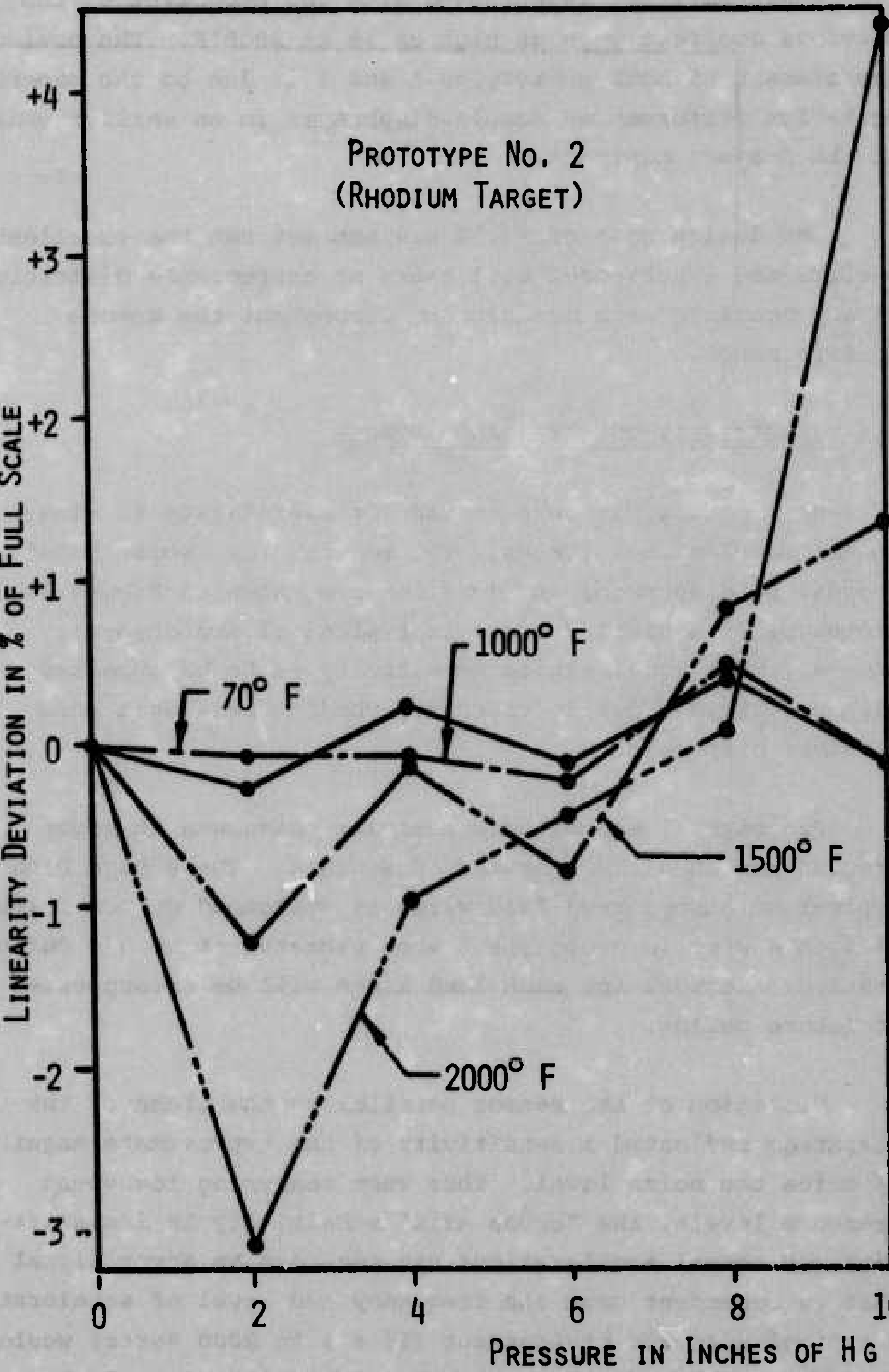


FIGURE 18. PRESSURE LINEARITY

Nonlinearities experienced with the prototype of the previous contract were as high as 7% at 2000°F. The obvious improvement of both prototypes 1 and 2 is due to the experimentation performed on sample diaphragms in an earlier phase of the subject contract.

The design goal of $\pm$0.1% was not met but the excellent performance experienced will cause no appreciable distortion of any acoustic wave measurement throughout the entire dynamic range.

7.4 <u>SENSITIVITY TO EXTRANEOUS FORCES</u>

Both prototypes were tested for sensitivity to sinusoidal acceleration forces. The results for "worst case" (normal to diaphragm) acceleration are shown in Figure 19 for prototype 2. A similar curve is typical of prototype 1; however, more acceleration sensitivity is to be expected with prototype 2 due to the dense rhodium mass on a more flexible diaphragm.

Prototype 1 exhibited a resonant phenomena at lower frequencies than the diaphragm resonance. These have been typical of unsupported lead wires as evidenced by the failure of such a wire in prototype 2 when vibrated at 50 g's during testing. Support for such lead wires will be incorporated in future builds.

Vibration of the sensor parallel to the plane of the diaphragm indicated a sensitivity of the approximate magnitude of twice the noise level. Thus when measuring low sound pressure levels, the "cross axis" sensitivity is insignificant but normal accelerations can generate an error signal that is dependent upon the frequency and level of acceleration. A typical aircraft environment (10 g's to 2000 Hertz) would introduce such a "worst case" error signal that would be less than 20 dB above the minimum detectable sound pressure level.

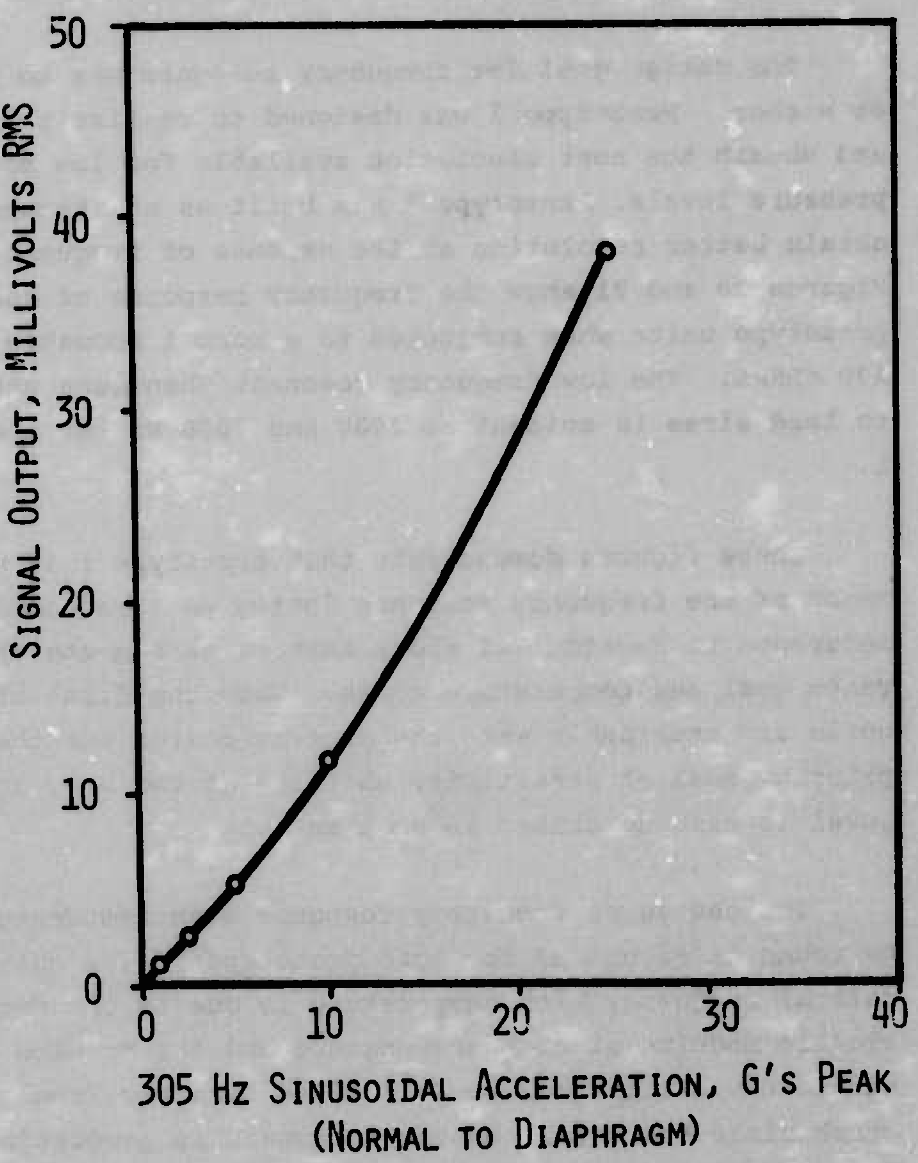


FIGURE 19. ACCELERATION RESPONSE OF PROTOTYPE NO. 2

7.5 FREQUENCY RESPONSE

The design goal for frequency response was to be 10 KHz or higher. Prototype 1 was designed to realize this response and obtain the best resolution available for low sound pressure levels. Prototype 2 was built as an attempt to obtain better resolution at the expense of frequency response. Figures 20 and 21 show the frequency response of these prototype units when subjected to a normal acoustic field of 130 dBSPL. The low frequency resonant phenomena attributed to lead wires is evident at 2000 and 7000 Hz for prototype 1.

These figures demonstrate that prototype 1 is within reach of the frequency response design goal required. Reference to Section 7.1 shows that it also meets the dynamic range goal and temperature goals. Thus the first three priority goals are attainable with the present design and the fourth priority goal of sensitivity shift is at the very tolerable level as also described in Section 7.1.

The change of frequency response with temperature can be found in Figure 22 for both prototypes. The change of natural frequency with temperature is due to the decrease of elastic modulus at high temperature and the modulus change versus temperature can be determined directly from this graph since the square of the frequency is proportional to the elastic modulus. Elevated temperature modulus data was previously not available from the deflection material supplier.

7.6 THERMAL TRANSIENT EFFECTS

Testing was limited by the available equipment to an average transient of 1.5°F/sec. When exposed to this transient, the sensitivity did not shift any more than the static values presented in Section 7.1. Since heat transfer becomes

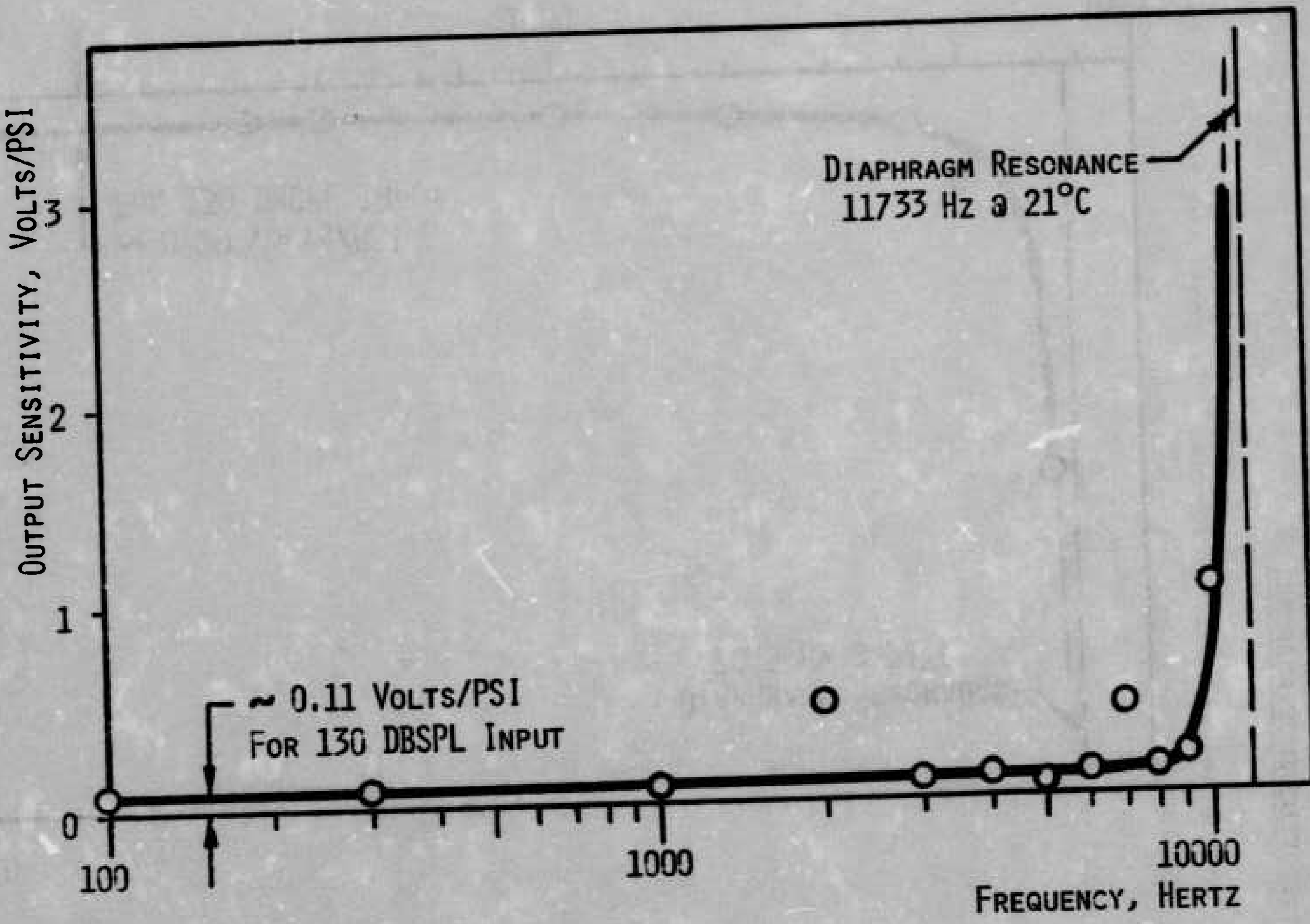


FIGURE 20. SENSITIVITY VERSUS FREQUENCY (PROTOTYPE NO. 1 @ 21°C)

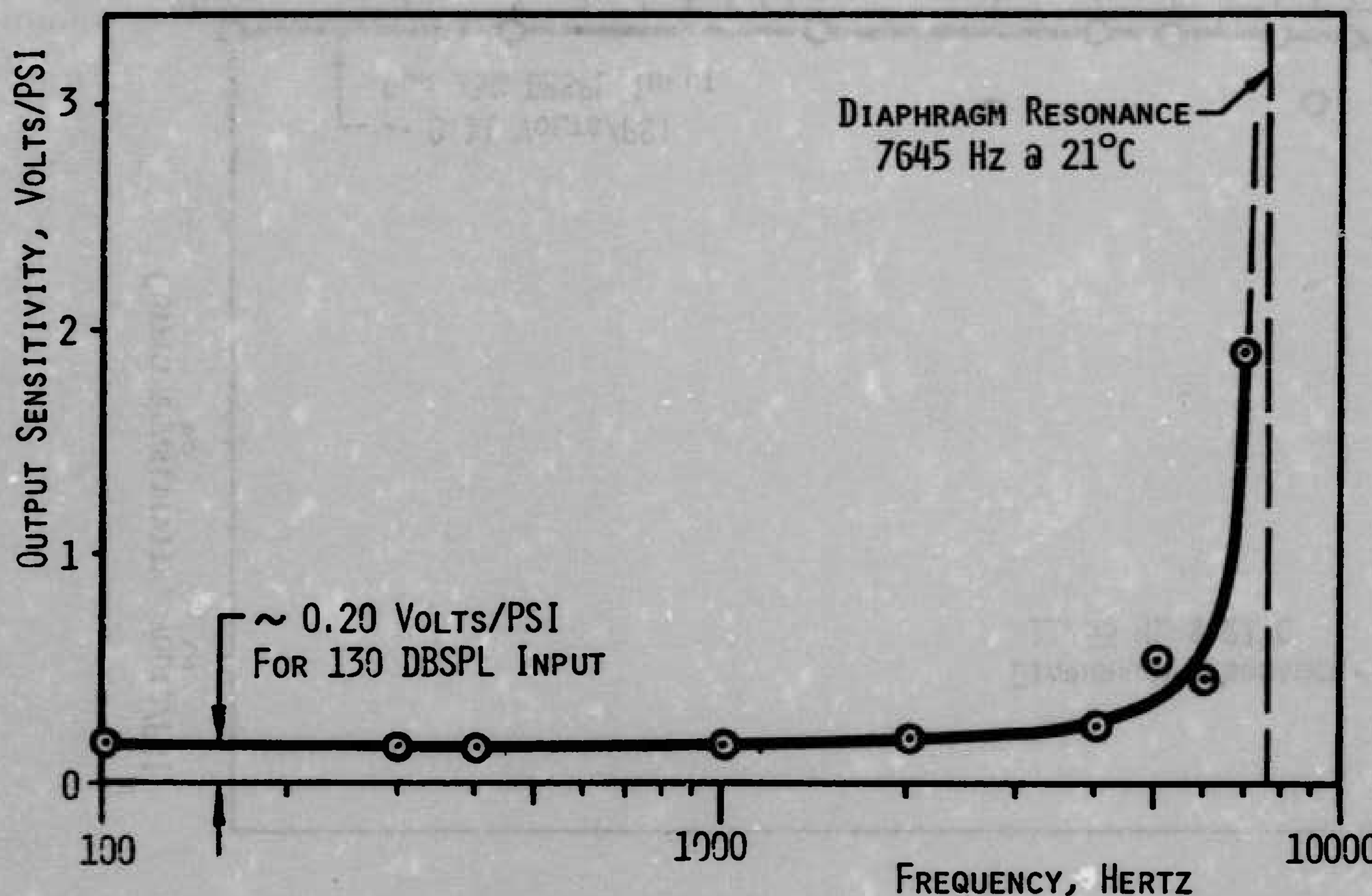


FIGURE 21. SENSITIVITY VERSUS FREQUENCY (PROTOTYPE NO. 2 @ 21°C

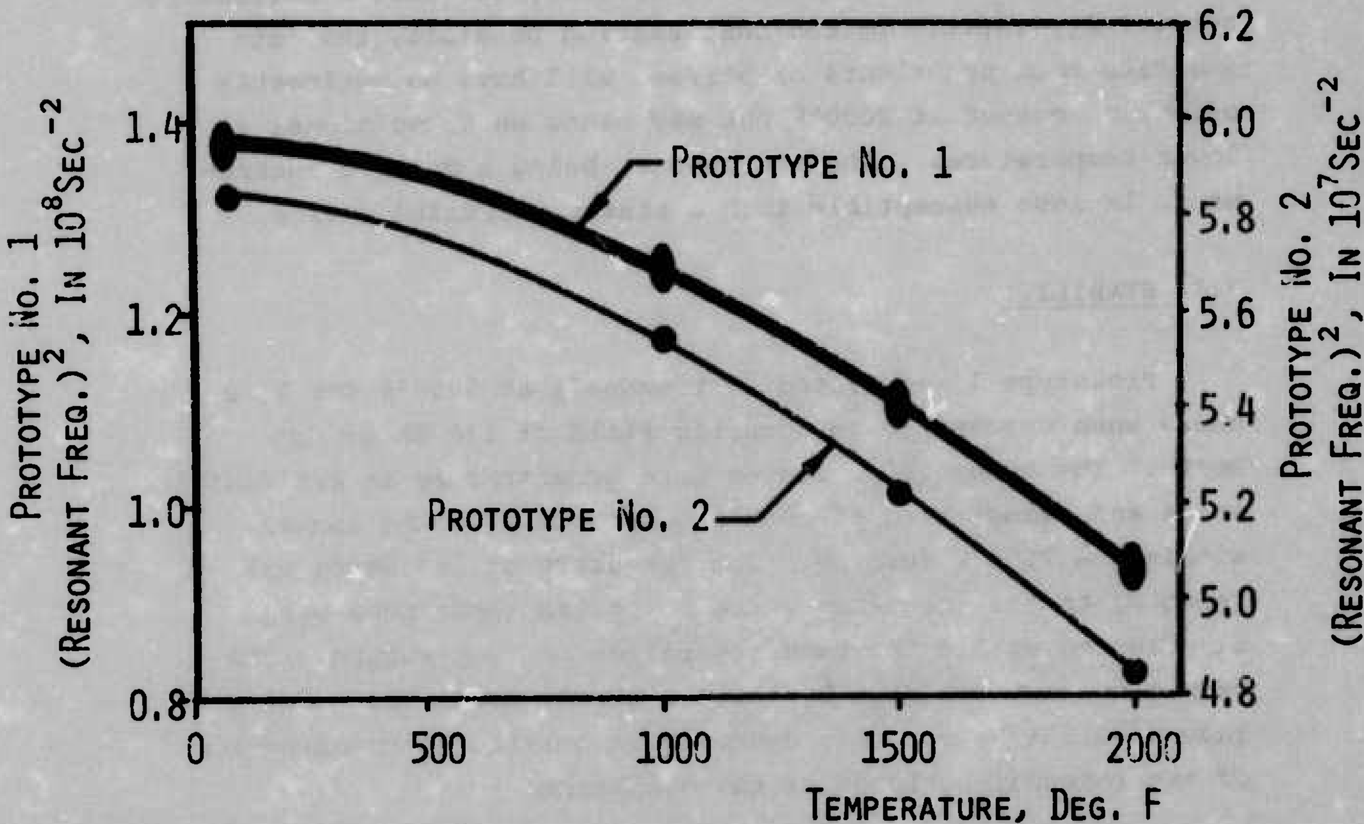


FIGURE 22. DIAPHRAGM RESONANT FREQUENCY VERSUS TEMPERATURE

faster at the higher temperatures due to radiation the transient response is temperature dependent, however, transients in excess of 1.5°F/sec would be necessary to cause a noticeable sensitivity shift. To the best testing possible, the data indicate that transients of 5°F/sec will have no noticeable effect on output at 2000°F but may cause an error signal at lower temperatures. The microphone, being a dynamic instrument, is less susceptible than a static measuring device.

7.7 STABILITY

Prototype 1 was tested continuously at 2000°F for 21.2 hours when exposed to an acoustic field of 130 dB at 305 Hertz. The acoustic pressures were generated by an artificial voice and transmitted through a quartz tube to the sensor within the 2000°F furnace. The frequency of 305 Hertz was selected as the frequency where no column resonances were experienced within the tube regardless of temperature. The output voltage was down by 11.1% after 21 hours for a shift rate of 0.52%/hour. This decrease is attributed to oxidation of the internal surfaces of the diaphragm.

This period of testing began after the sensor had been at 2000°F for approximately 41 hours. After 62 hours at 2000°F, the sensor is still performing satisfactorily.

7.8 AREAS OF PERFORMANCE TO BE ADVANCED

Two basic areas require changes for improved performance of future units. They are frequency response and low frequency resonances.

The decision to build and test two different prototypes proved to be very valuable in establishing what trade-offs can be made to realize adequate dynamic range and frequency response. Since the 100 dB dynamic range goal was realized with both prototypes (120 dB for prototype 2) it is now verified that an increase of the frequency response to a 10 KHz band at 2000°F can be attained with 100 dB dynamic range. This change is planned for any future units.

The frequency band should also be made free of resonances below the first mode of diaphragm resonance. This will be obtained by fixing all unsupported leads and deflecting elements of the sensor.

In general the performance of both prototypes was found to be excellent when the extreme temperature range is considered. The first three priority goals are attainable and the others were met to a level that compares with performance of typical laboratory standards. Most importantly, a useful instrument system has been developed and performance proven which was the primary goal of the program.

TABLE 6. DESIGN GOAL AND PERFORMANCE COMPARISON

	DESIGN GOAL	PERFORMANCE Prototype 1	PERFORMANCE Prototype 2	REMARKS
1.	Sensitivity changes of less than ±0.5% -65°F to 2000°F	+2.15% -3.48%	+1.87% -1.23%	Design goal not met but improvement from Contract F33165-72-C-1199 is significant.
2.	Dynamic range of 100dB	100dB	120dB	Design goal met and exceeded
3.	Output linearity 0.1% over entire dynamic range	+1.75% -2.8%	+4.4% -3.1%	Considerable improvement over previous contract value of ±7%
4.	Insensitive to other measurands by less than 1%	Within 1% from low frequency to 2000 Hertz at a maximum acceleration of ±10 g's peak to peak		Test instrumentation system noise problems made some data inconclusive. Data based on worst case microphone (Prototype 2)
5.	Cross axis sensitivity to other measurands by less than 1%	Sensitivity appromately 1/10 of the in-line axis sensitivity		Frequency and acceleration limits would be dependent on the internal resonances noted and discussed
6.	Frequency response of 2 to 10,000 Hz	2 to approx. 9000 Hertz @2000°F	2 to approx. 6200 Hertz @2000°F	Design goal can be achieved if adjustments in diaphragm thickness are made. 100dB dynamic range could be maintained
7.	Thermal transient response of less than 10dB above minimum output for transients of 5°F/second or less	No effect noticeable with transients of up to 1.5°F/second		Testing capability limited to 1.5°F/second
8.	High degree of stability	Stability shift of 0.52% per hour @ 2000°F		2000°F stability felt to be excellent
9.	Transducer size of .75 cubic inches or less	Volume approximately 0.15 cubic inches		Design goal exceeded
10.	External power held to a minimum	+15 volts DC, ±1/2 volt DC regulation 55 mA typical current		Design goal achieved
11.	External circuitry held to a minimum	Minimum external circuitry required		Design goal achieved
12.	Microphone range of 20-120dBSPL and 90-190dBSPL	Microphone range of 90 to 190dBSPL achieved		Practical design limitations exclude 20 to 90dBSPL range. 90-190dBSPL range achieved

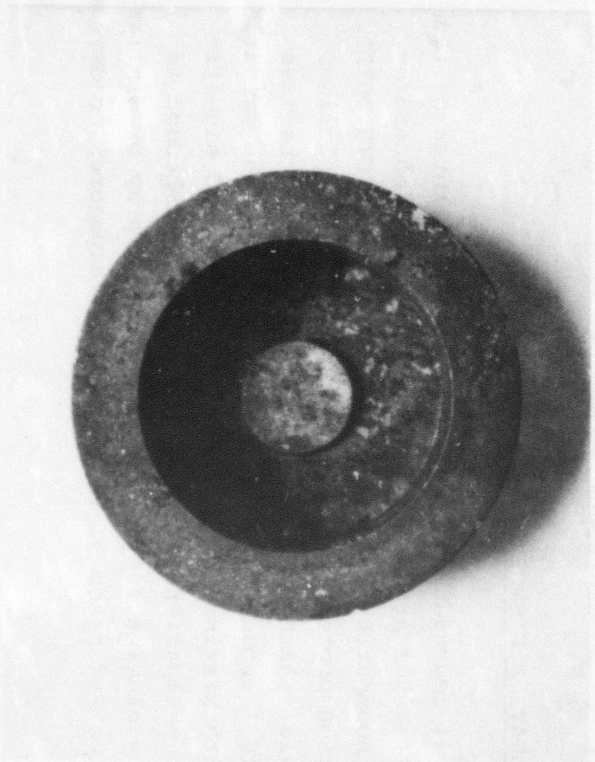
8.0 SERVICE LIFE VERSUS TEMPERATURE

8.1 ESTIMATE OF USEFUL LIFE

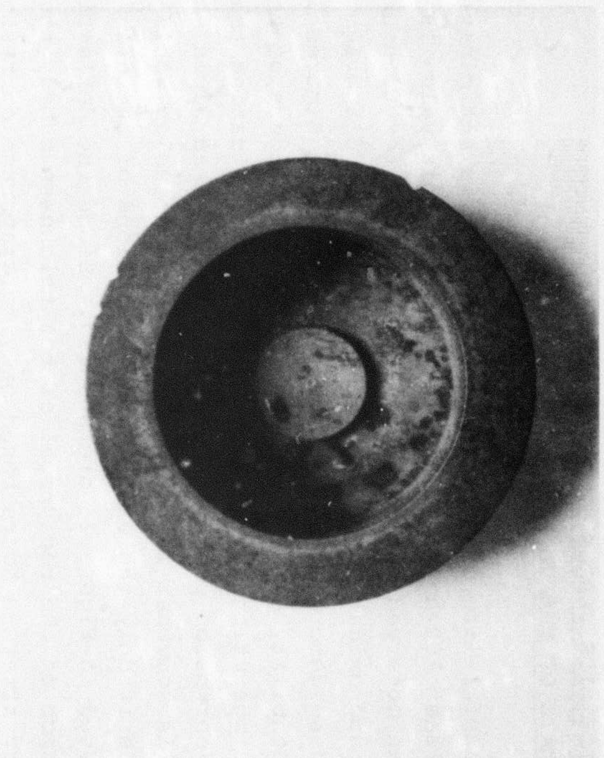
The useful life of the microphone sensor is anticipated to be at least 100 hours at 1093°C(2000°F). This value is based on an observed performance of prototype 1 for 62 hours at 1093°C and oxidation data gathered during the diaphragm testing phase described in Section 5 and shown in Figures 23 and 24. Stability data taken between 41 and 62 hours of the transducer operation were exceptionally good indicating that the total corrosion processes of the coil and lead wires and diaphragm is somewhat in balance. Such a conclusion would not be made if only the oxidation penetrations of the diaphragms noted in Figure 24 are studied. Since the deflection is a function of the reciprocal of the thickness cubed, the sensitivity after 50 hours based only on diaphragm corrosion of 0.0008 inches per side would be increased over 200%. Evidently the composite structured diaphragm (metal plus oxide layer) behavior as well as coil and lead wire deterioration are factors which tend to offset the theoretically increased flexibility of the diaphragm.

8.1 DEGRADATION HISTORY OF DESIGN FEATURES

Thermal degradation of various design features of the microphone sensor are mainly limited to oxidation and/or chemical incompatibility of materials. At 1093°C(2000°F), the oxidation process even takes place with the platinum group metals. Although quoted in Reference 1 to be less than 1×10^{-5} thousandths of an inch per hour, the oxidation process with platinum above 1000°C is considered significant. Recommendations are that the wires be imbedded in high purity alumina refractory by a plasma spray or similar process (see Reference 2) to inhibit the exposures to oxygen.

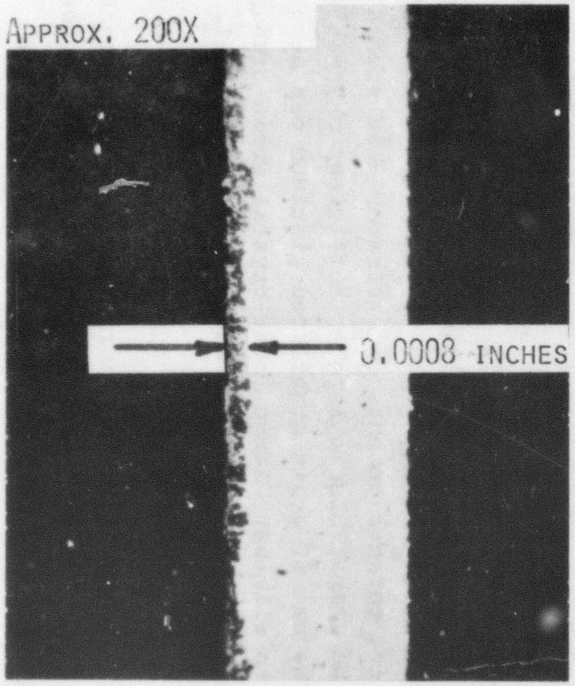


HAYNES # 8077 ALLOY
50 Hours at 2000°F



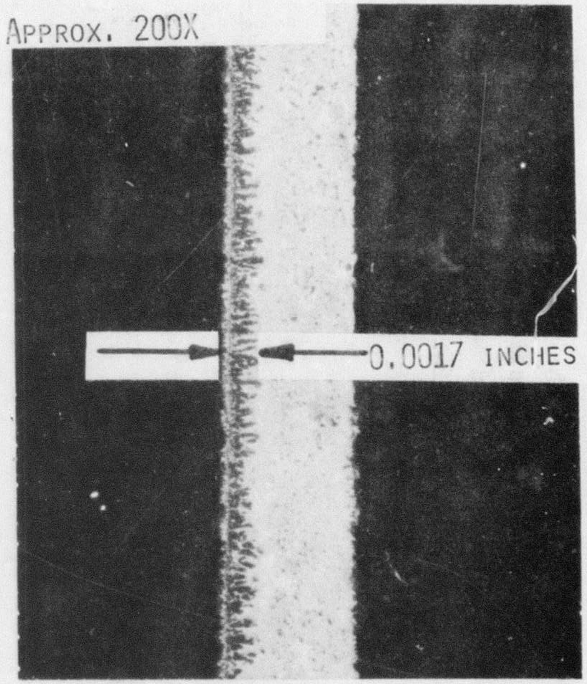
HAYNES #8077 ALLOY
100 Hours at 2000°F

FIGURE 23. DIAPHRAGM TEST SPECIMENS



50 Hours at 2000°F

Haynes #8077 Alloy



100 Hours at 2000°F

Haynes #8077 Alloy

FIGURE 24. TEST DIAPHRAGM SECTIONS

Coating and encapsulation of the sensor lead wires should aid in two respects; (1) reduction of oxidation processes and (2) elimination of the lead wire resonance noted during vibration testing. At this point, oxidation of the lead wires is not a major problem; however, the foregoing process should be considered.

The chemical incompatibility at 1093°C(2000°F) of the conductor wires and the surrounding media present a far greater problem. After a careful review of the technical literature, manufacturers and suppliers data, it is concluded that platinum or platinum group metals do not survive well in any environment except one that is highly oxidizing. Inert, vacuum or reducing environments are detrimental to use of the platinum metals. An oxidizing environment would be most suitable with the platinum metals only in contact with high purity alumina which is exceptionally chemically stable at these temperatures. The presence of silicon should be avoided (see Reference 2) since it readily attacks and imbrittles platinum group metals. In Reference 3, the reduction of silica (SiO_2) to silicon and oxygen in the presence of helium is noted at 1300°C. Our 62 hour success with a platinum-rhodium conductor, silica insulation and silica bearing ceramic cements demonstrates that such a system can be compatible as long as sufficient oxygen is present. The use of grain stabilized platinum can also be considered to eliminate large inter-crystal grain boundary failures noted in Reference 2. Such platinum materials are available.

The final and most severe corrosion problem is that of the deflection material (Haynes Alloy #8077). Oxidation behavior with time is listed below:

Time (hours)	Oxidation Penetration (inches per exposed side)
25	.0004
50	.0008
100	.0017

The specimens for these measurements were part of a dynamic test evaluation (see Figure 23). The near linear oxidation behavior is somewhat higher than measured on the previous contract or expected from analytical considerations. The only explanation for a somewhat increased oxidation behavior when compared to passive oxidation, would be the dynamic stress situation. This would promote preferential corrosion along the highly stressed grain boundaries and would also permit fracturing of the oxide protective barrier allowing oxygen to readily diffuse to the unoxidized metal.

The diaphragm oxidation is probably the most critical factor in the overall service life. Dispersion strengthened superalloys have exceptional oxidation resistance at 1093°C but considerable work in the gas turbine industry is noted concerning protective coatings for superalloys. Use of a protective coating presents the only hope of significantly extending the expected 100 hour life.

9.0 EXTENSION OF THE CONCEPT TO OTHER MEASURANDS

9.1 ACCELERATION

The extension of the eddy-current microphone sensing technique to measure acceleration is relatively simple and is discussed in length in Kaman Proposal KS-74-307 submitted to the AFFDL/FYT at Wright-Patterson on 9 August 1974. Briefly, the basic design would be based on Kaman's KA-1901 accelerometer presently being marketed for use at 649°C(1200°F). Such an accelerometer design would offer minimal technical risks since the problems of extending the technique to 1093°F(2000°F) have successfully been demonstrated and the design details of a 649°C accelerometer and associated electronics have been accomplished. The design details would be similar to the KA-1901 accelerometer shown in Figure 25. The detection element of this figure is a seismic mass connected to a cantilever beam that responds to acceleration and thus the change in magnetic coupling between a flat coil and the induced eddy currents of the conductive plate allows an electronic detection of acceleration to be made.

Two coils and two conductive plates are employed in order to balance the effects of the general environment excluding acceleration. One coil and one conductive plate are mounted on each side of the cantilever beam. This particular symmetrical geometry doubles the sensitivity since as the mass moves towards one coil it moves away from the other. Since the each coil is in an arm of an impedance bridge, the unbalance of the bridge is doubled when compared to the single coil unbalance necessitated by the exposed deflection member of a microphone or pressure transducer. The signal conditioning electronics would be very similar to the design used for the 1093°C microphone system.

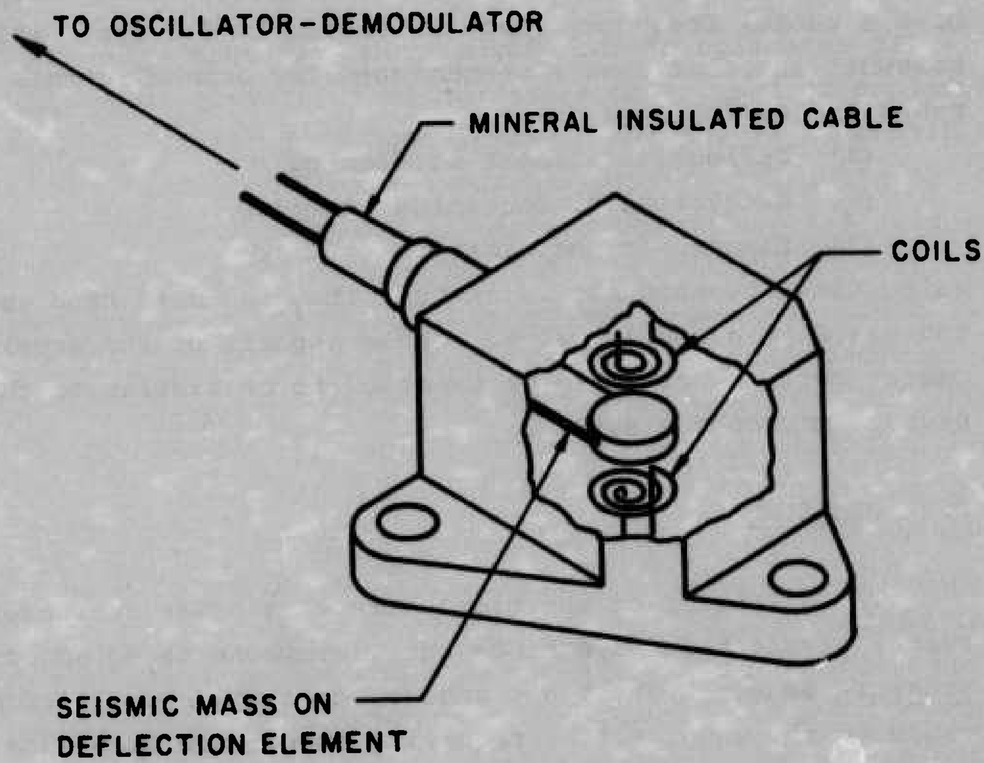


FIGURE 25. HIGH TEMPERATURE (650°C) ACCELEROMETER

The major deficiency of such an accelerometer design is its useful frequency response range. In the extension of the design to a ± 1000g range, the transducer would only have a useful frequency range extending to 2.1 KHz. This is somewhat low, but several techniques for extending this range are as follows:

(1) Deflection element stiffening

(2) Electrical or mechanical damping

(3) Electronic compensation

Using these techniques, it is felt that the data band can be increased to a usable value. Other aspects of the accelerometer performance would be expected to be similar to the present microphone system.

9.2 PRESSURE

The extension of the microphone to a pressure sensor is rather straight-forward since the microphone is an acoustic pressure sensor. The basic sensor, cabling, and electronics would be the same. Items requiring change are diaphragm design to reduce stresses at pressures higher than one atmosphere and reduction of thermal zero shift caused by trapped internal gases within a sealed sensor. Both of these changes may dictate a larger sensor than the 1/2 inch diameter unit used as the microphone element.

9.3 FORCE

A 2000°F force transducer will again be similar to the microphone but some differences are noteworthy. The deflection element must be stiff to obtain a range of 1000 pounds but it must also provide deflection at a minimum stress. A method of obtaining such an element is to utilize a refractory alloy in a "folded" spring configuration similar to Kaman's design of a zero pitch spring. The refractory metal must be protected from the atmosphere and this protective barrier must still be capable of transmitting the applied force. A metallic bellows fabricated from an oxidation resistant material would be used to satisfy this requirement. The same eddy current principles would be used, including coils, cabling, and electronics. A concept sketch is shown in Figure 26.

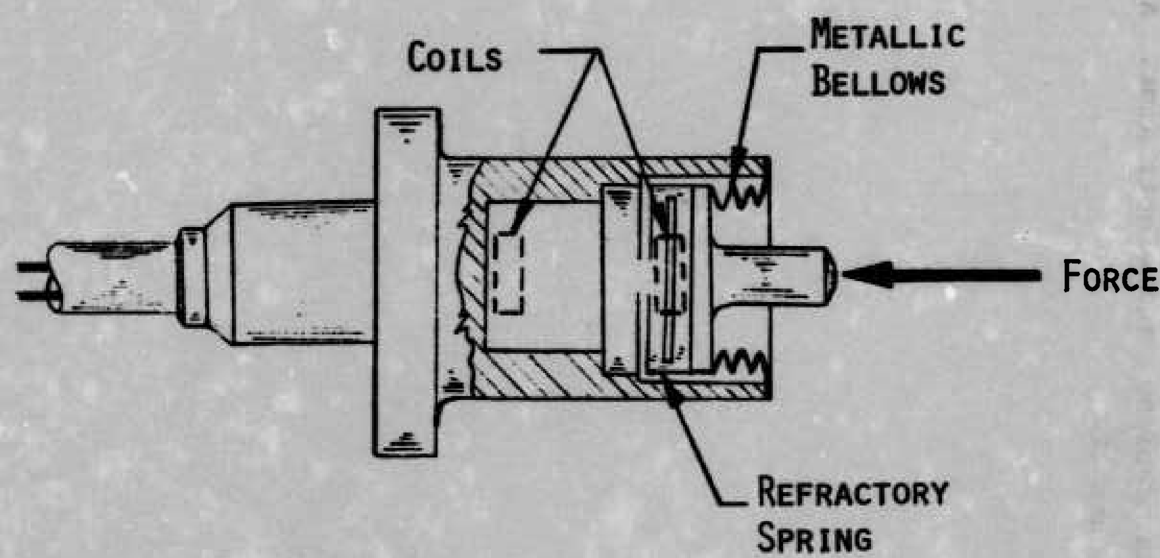


FIGURE 26. CONCEPT OF 2000°F FORCE TRANSDUCER

10.0 INDEPENDENT GOVERNMENT TESTING AND USE

10.1 INTRODUCTION

The 1093°C(2000°F) microphone system that is required by the work statement is illustrated in Figure 27, where the major parts of the system are identified. The basic system represents an extension of Kaman's high temperature pressure measuring systems which involved the continued development of a sensor and cabling for use at 1093°C (2000°F).

The general operating characteristics of the system are given in this section; however, the staff of Kaman Sciences Corporation is available for consultation concerning aspects of the system that may not be included within the scope of this section. This section is intended to provide the basic information that is necessary for the operation, installation and servicing of the prototype microphone measuring system in support of the independent Government tests. The system consists of precision instrumentation and it must be handled accordingly, especially the diaphragm.

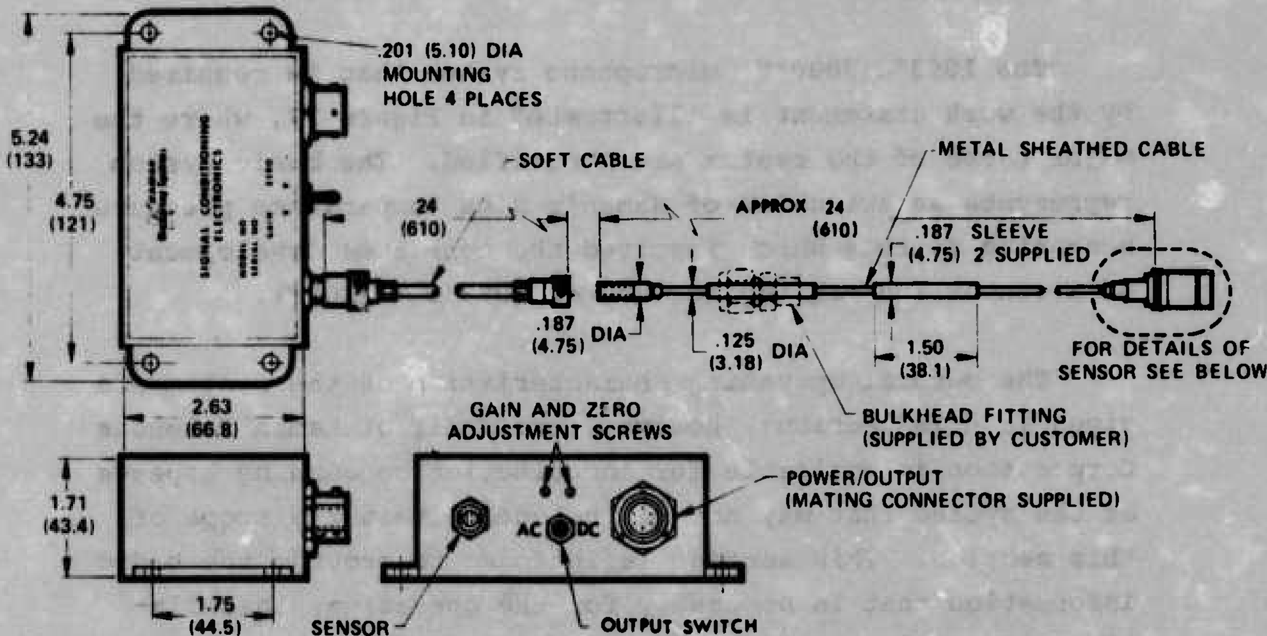
It is strongly recommended that this complete section be studied prior to adjusting or operating the system in any manner.

The signal conditioning electronics is illustrated in "block diagram" form in Figure 28. This figure shows how the input power is transformed by an oscillator to form a 1 MHz drive voltage for the sensor bridge. The impedance differences of the bridge are amplified and then detected by a demodulation of the 1 MHz carrier signal to provide a d.c. voltage output that is proportional to the impedance change of the bridge.

Kaman's KP-1910 electronics system has been designed for ease of operation. However, as with most test and measuring equipment, the operator can optimize system

SYSTEM CONFIGURATION

DIMENSIONS ARE MAXIMUM LIMIT IN INCHES (MILLIMETERS)



SENSOR CONFIGURATION

DIMENSIONS ARE MAXIMUM LIMIT IN INCHES (MILLIMETERS)

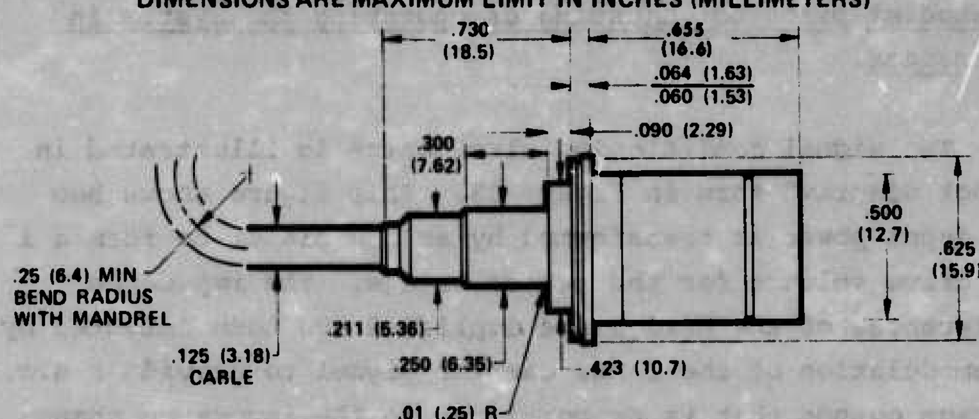


FIGURE 27. SYSTEM AND SENSOR CONFIGURATIONS

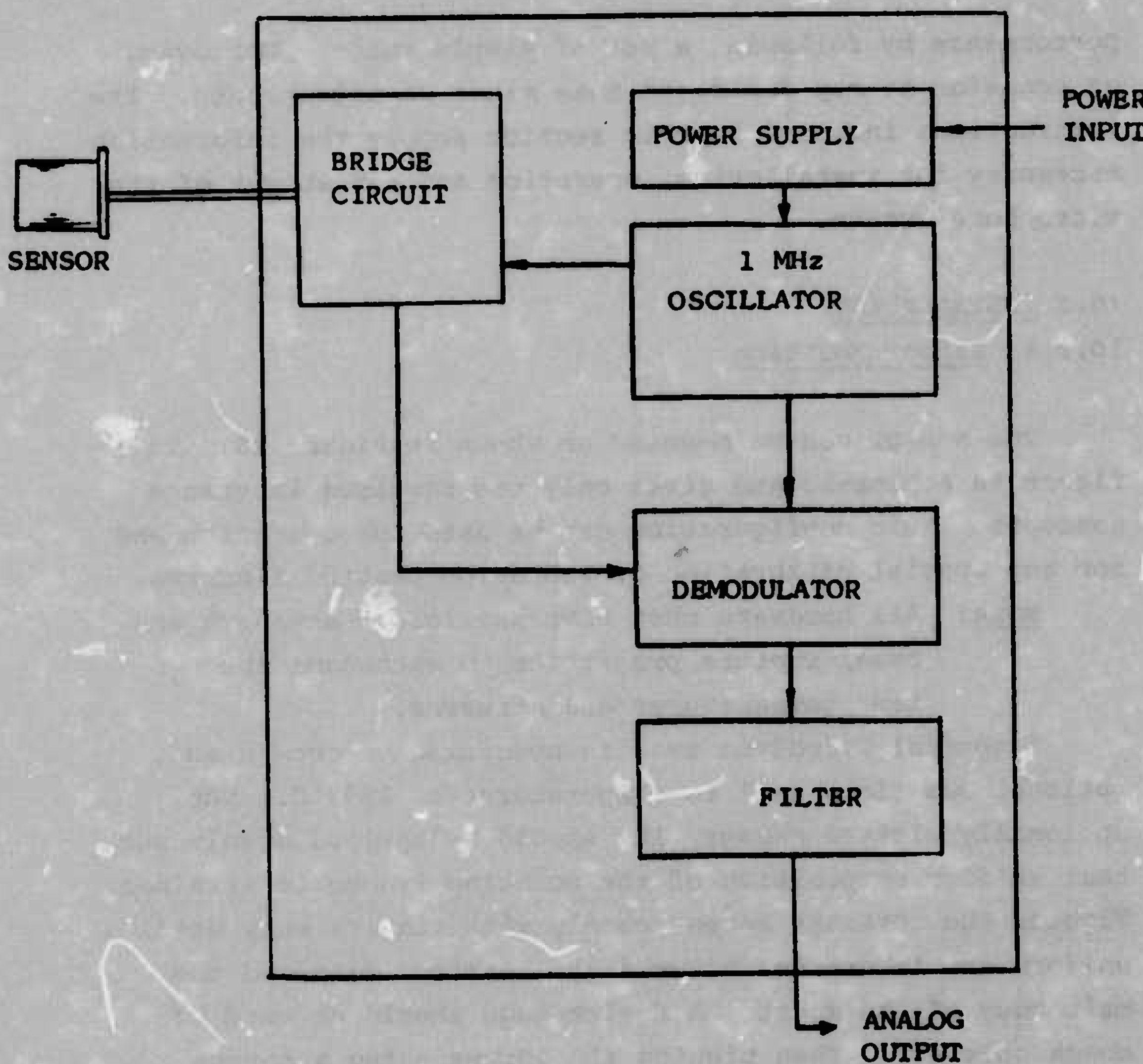


FIGURE 28. SIGNAL CONDITIONING ELECTRONICS

performance by following a set of simple rules. Moreover, on occasion he may desire to make minor re-adjustments. The instructions included in this section supply the information necessary for installation, operation and adjustment of the microphone system.

10.2 INSTALLATION

10.2.1 Sensor Mounting

The sensor can be mounted as shown in Figure 29. This figure is schematic and gives only the required interface concepts. This configuration can be used for operation and for any special calibration or vibration testing fixtures.

Note: All hardware must have sufficient strength and creep-rupture properties to withstand the test temperatures and stresses.

A special Hydrodyne seal is specified to obtain an optional gas tight seal to temperatures of 1093°C. The optionally slotted chaser ring should be applied evenly such that uniform compression of the mounting flange is attained. Tighten the retainer screws evenly with fingers only until a uniform gap is present between the retainer ring and the main body of the mount. A feeler gage should be used to check this gap. Then tighten the screws using a torque wrench if possible or approximately 1/8 turn at a time going in an opposite sequence of 1 - 3 - 2 - 4 if numbered consecutively around the flange. If more screws are used, use a similar sequence to alternately tighten opposite screws. Continue until all screws are tight. Use safety wire if desired for vibration requirements to maintain the torque of the screws.

The sealing surfaces of the ring, sensor and mount must be thoroughly cleaned with a solvent prior to assembly. If the flange of the sensor or mount has been scratched or damaged, it should be polished prior to assembly.

NOTE: ALL HARDWARE MUST HAVE SUFFICIENT STRENGTH AND CREEP-RUPTURE PROPERTIES TO WITHSTAND THE TEST TEMPERATURES AND STRESSES. MATERIALS SHOULD BE SELECTED ACCORDINGLY.

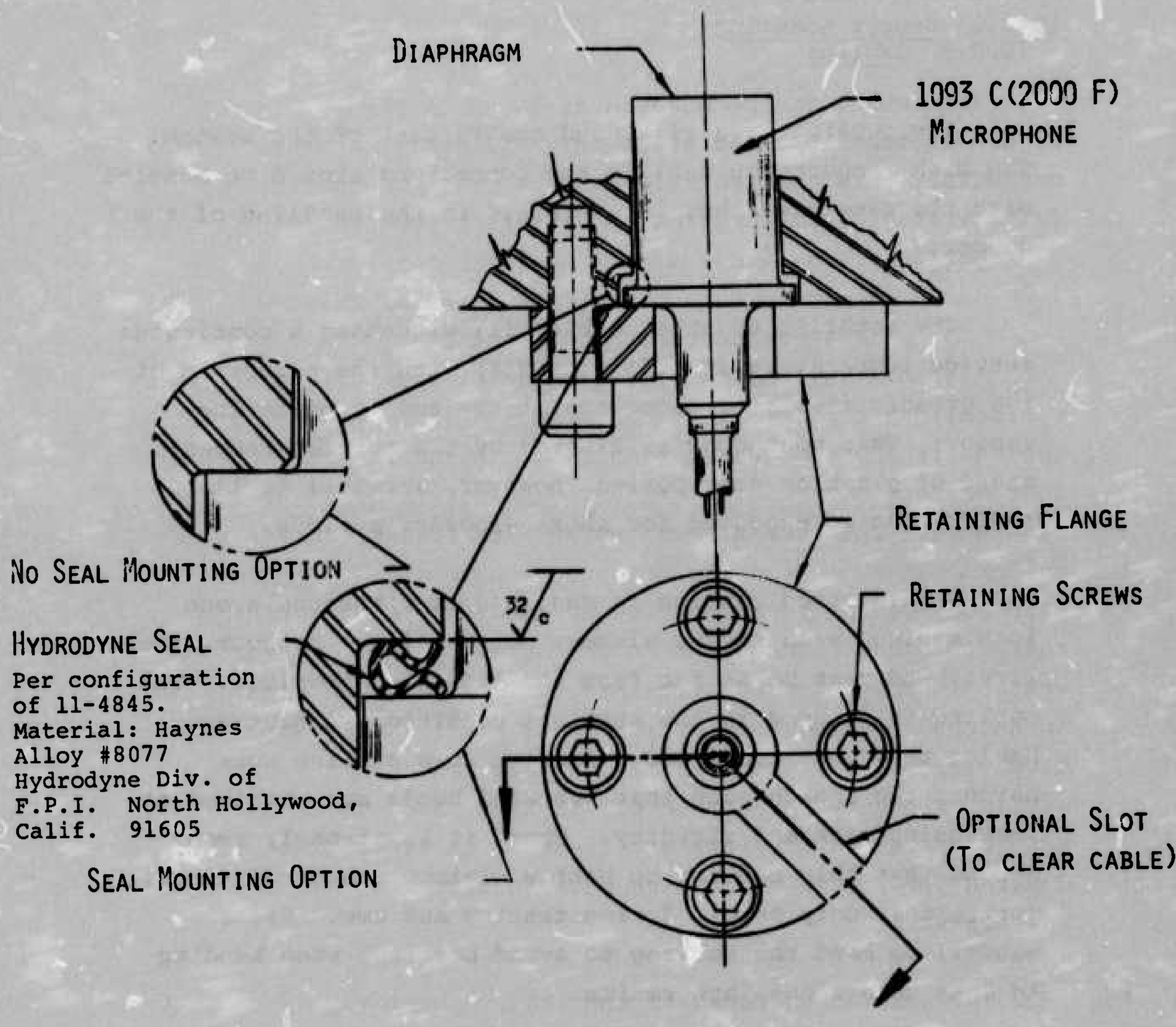


FIGURE 29. SUGGESTED MICROPHONE MOUNTING

Contamination moisture and solvents must be excluded from entry into the vent hole at the rear of the sensor as this will degrade performance. Use protective caps or plugs when performing mounting, polishing or cleaning operations.

Note: The diaphragm, (end of sensor), is extremely fragile. Any non-uniform deflection (dent) may irreparably damage it.

10.2.2 Cabling

The cabling is a vital and costly part of the system. The high temperature cabling and connectors should be handled with the same care that is exercised in the handling of the sensor.

The metallic sheathed cable will withstand a continuous service temperature of 1093°F(2000°F) with the exception of the organic insulated connector at the end opposite the sensor. This connector is limited by the service temperature of plastics and epoxies, however, survival to 149°C (300°F) can be expected for short exposure periods.

The sheathed cabling is designed to withstand a one inch minimum bend radius without degradation; however, the first bend must be as far from the sensor as possible. The cabling is shipped in the straight condition without ever having been bent or coiled. Bending this cabling work hardens the sheath such that repeated bends are obtained at increasing risk and rigidity. Thus, it is strongly recommended that this cabling be bent a minimum number of times, (preferably only once), during testing and use. Use a mandril to bend the cabling to avoid buckling when bending in less than a one inch radius.

Insulated clamps should be used to fasten this cabling at intervals consistent with vibration requirements. Proper fastening will prevent shorts and vibration fatigue. The clamps should have no sharp edges that would cut the sheath or otherwise damage its surface.

Since the sheath of the cable is normally at ground potential, (and this is vital to the operation of the transducer) care must be exercised to avoid having this cable "short out" other circuits. The cable sheath must not short itself if a loop is employed since this will cause a slight shift of the output. As a general rule, the cable should be completely isolated from ground points between sensor and signal conditioning electronics for best operation.

10.2.3 Signal Conditioning

The signal conditioning case has two flanges with two holes in each flange for mounting. These four holes are 0.201 inches diameter which makes them suitable for standard fasteners (no. 10, 0.190 inch diameter).

10.3 ELECTRICAL CONNECTIONS

The metal sheathed cable is connected to the flexible (soft) cable by means of a special indexed connector shown in Figure 30. This connector is designed to be rugged and small such that the pins are protected from normal handling damage. The sockets are recessed into a threaded sleeve that is permanently welded to the metal sheathed cable. This connector can be panel mounted if desired by using #10-32 NF nuts as shown in Figure 31.

To make the electrical connection, simply insert the "half-moon" shaped tab on plug into the "half-moon" groove in receptacle and tighten the knurled nut until finger tight. Do not force with pliers or similar tools. If vibration is expected, a liquid thread locking material can

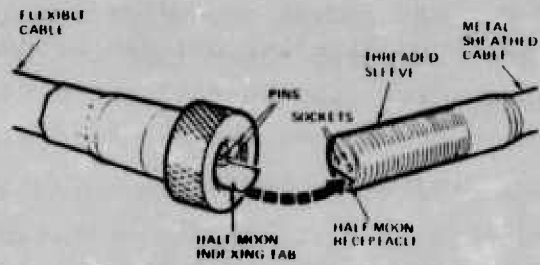


FIGURE 30. CABLE CONNECTOR

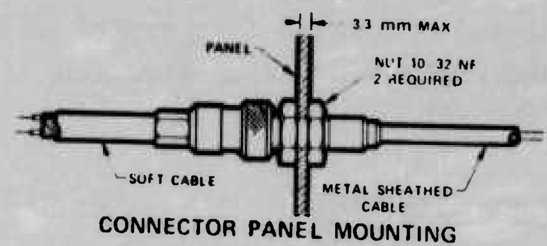
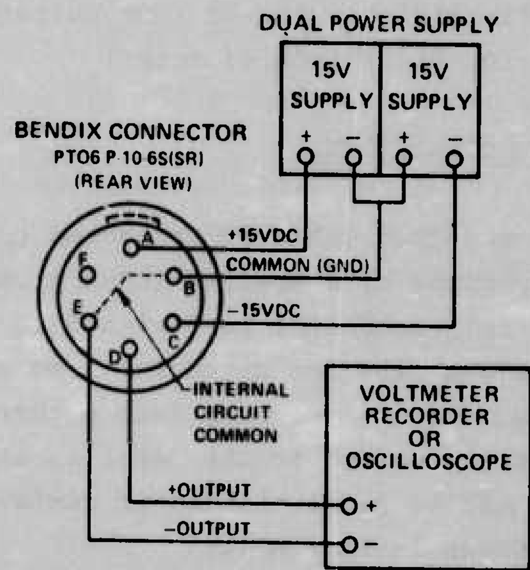


FIGURE 31. CONNECTOR PANEL MOUNTING



PIN	FUNCTION
A	+ 15Vdc (Positive supply input)
B	Ground (Supply input common)
C	− 15Vdc (Negative supply input)
D	+ Output
E	− Output (common with ground)
F	No connection

FIGURE 32. POWER/OUTPUT SCHEMATIC

be used or alternately a #10-32NF nut can be jammed against the knurled nut; however, the knurled nut must always remain tight against the end of the threaded sleeve in order to maintain a firm electrical contact.

The other end of the soft cable has a larger connector indexed with a plastic "half-moon" tab and a slot. This end is connected to the mating connector on the electronics package and the knurled nut again tightened finger tight only.

10.4 POWER/OUTPUT CONNECTIONS

The input power requirements are + and -15Vdc ($\pm$0.5Vdc) at 55 mA. The Kaman Model P-3200 (for powering one to six units) or the Model P-3300 (including digital voltmeter with six channel selector switch) is recommended, although any 15 volt d.c. regulated dual supply can be used. The POWER/OUTPUT cable can be mated directly with the KP-1910 electronics package (bayonet mount) and the cable end leads are identified for connection to the power supply and readout instruments.) The electrical connections are shown in Figure 32. Output connections to a voltmeter, recorder, oscilloscope, or other readout device should be made as shown.

10.5 INITIAL CHECKOUT

The initial checkout is limited to checking the "zero" setting unless sound pressure can be applied to the sensor. If sound pressure and/or temperature are to be applied, the sensor should be mounted as described previously and then the operation instructions should be followed for the checkout.

Assuming sound pressure level is not available for this initial checkout, keep the protective cap over the sensor and connect the system as described in the previous section.

Put the output switch in the DC position. Apply the + and - 15 volts d.c. power and allow approximately 10 minutes for warm-up. The microphone system should indicate zero output voltage equivalent to zero static gage pressure level. If readings other than zero are indicated as the output, insert a small screwdriver into the "ZERO" opening of the electronics package where a small screwdriver slot is recessed within the case by approximately 0.40 inches. Rotate adjustment slightly to obtain the proper output. If the proper output cannot be attained, recheck all connections and again adjust the "ZERO". If the proper output is still not obtained, refer to Section 10.9 "Troubleshooting." Put output switch in AC position and refer to the data of sound pressure level vs. output for measurements.

10.6 OPERATION

With the system properly mounted as described above, it is ready for operation. The power that is supplied to the power/output connector supplies power for the complete system. Allow a warm-up period of 15 minutes if possible to realize equilibrium temperature within the electronics for best stability of operation.

The media to which the diaphragm of the sensor is exposed should be free from directly impinging projectiles such as sand and dust. Severe thermal transients should also be avoided where possible since stability depends upon the time rate of change of the sensor temperature.

10.7 CALIBRATION PROCEDURES

The complete calibration is accomplished prior to the system's leaving the manufacturer. During this final calibration the selected components are installed for matching the electronics, cabling, and sensor. These values are selected to provide the minimum values of thermal shifts of both zero and sensitivity. It is vital to the system operation that the system be connected as shown with consistent cable connections. The cables cannot be shortened or additional lengths added or omitted without altering the calibration, performance, and compensation that has been installed at Kaman.

Details for checking and making fine adjustments to the calibration are described in what follows:

a. The sensor should be installed in a test fixture which can provide a sound pressure level of 190dB or a quasi-static square wave signal of ±9.17 psi at 3 Hertz. This fixture should then be put in an appropriate heat source such as an oven or furnace that can be temperature controlled. The output voltage switch should be in the AC position.

b. Power is then applied to the electronics. Allow a period of 10 minutes for warm-up and stabilization if possible.
The output can be read by a suitable recorder or voltmeter at the output connector.

c. With zero dB applied to the sensor, and the output switch on AC, the output should be zero.

d. Apply full scale sound pressure level. As this signal is observed, adjust the "GAIN" such that the output is full scale. Full scale output at 190dB for Prototype 1 and 2 is as follows:

Temperature	Prototype 1	Prototype 2
R.T.	1200 mV	4200 mV
1000°F	800 mV	2150 mV
1500°F	620 mV	1400 mV
2000°F	790 mV	1500 mV

Static testing at 1093°C(2000°F) is not recommended above 5 psi. Creep and distortion of the thin diaphragm would result.

e. Check the zero level and recycle steps c and d if necessary

f. The gain and zero can be set at any desired sensor temperature to obtain the best characteristics for the operating conditions. Note: The "zero" adjusts for static offset only.

10.8 MAINTENANCE

The sensor is an irreversibly sealed unit and consequently, routine maintenance is limited to care and cleaning.

The appearance of the sensor is that of oxidized metal due to the operational temperature. Any foreign matter other than these oxides should be removed. The following steps should be used as a guide.

a. Note: The diaphragm (end of sensor) is extremely fragile. Any non-uniform deflection may irreparably damage it. The diaphragm should never be touched or contacted with anything other than fluids or gases.
b. To clean the diaphragm, bathe it with a suitable solvent for the contamination and blow it with a mild air blast from the side, keeping the air source at least six inches from the diaphragm. Repeat as necessary. Use only filtered air such that no particles will blast the diaphragm. The air pressure should not exceed 25 psi.
c. The remainder of the sensor can be wiped with solvents and blown dry using the same techniques given in a and b above. Protect the mounting flange sealing surface from scratches or flaws that may impair its sealing function. Use care to avoid getting solvents and contaminants into the sensor vent holes. This could degrade the performance of the sensor.
d. Connections are subject to contamination under repeated use. These should be inspected for foreign matter on the contacts and should be cleaned with an electronic contact cleaner as required. The connectors on the soft cabling should be checked

for fit to the cabling since organic materials creep and they may tend to become loose. They should be tightened or rebuilt if necessary. Alteration of lengths of this cabling for connector repair will alter calibration. The calibration should be checked if such a repair is required. A factory compensation may be required if the calibration cannot be retained.

e. Maintenance of the signal conditioning electronics is limited to cleaning also. The connector contacts should be cleaned with electronic contact cleaner periodically, especially if disconnected repeatedly.

10.9 TROUBLESHOOTING

This section provides a guide for isolating the cause of malfunctioning of the sound pressure measuring system. The sensor can be checked for coil integrity as follows:

1. Disconnect the solid sheathed cable from the soft cabling at the Kaman connector.
2. Using an ohmmeter that does not have a battery of voltage greater than 1.5 volts, check continuity from each pin of the connector to the sheath. The values should be approximately 16 ohms at room temperature and the value from pin-to-pin should be twice this value. Values grossly larger or smaller than these values indicate a faulty sensor assembly.
3. Check all connectors for cleanliness and make certain that contact is being made. Clean if necessary.
4. Contact Kaman Sciences if other difficulties are experienced.

11.0 CONCLUSIONS

A significant advancement of 1093°C(2000°F) microphone system technology was made. The objectives of the effort to complete the design, incorporate minor improvements and obtain performance and service life definition were all accomplished.

Three of the four design priorities of the program including operation to 1093°C, response of 2 to 10,000 Hertz and dynamic range of 100dB were accomplished. The fourth priority, thermal sensitivity shift, was not met, but was considerably improved from the previous contract and is at a very tolerable level. The remaining design goals have likewise been exceeded, met or are at a most acceptable value. In all cases, improvements are noted in the performance of the prototype microphone systems when compared to the previous contract effort.

The microphone system design now exists in a most useable configuration for Air Force testing plans. Design improvements include (1) a chemically stable ceramic cement, (2) a diaphragm design based on dynamic testing at 1093°C, (3) a thermally stabilized high temperature cable insulation and ceramics, (4) a low cost cable sheath, (5) a high sensitivity rhodium button design, (6) a cost effective sensor design based on ease of fabrication and assembly, and (7) a compact, reliable and low noise electronics package.

The useful life of the microphone sensor has also been established. With combined experimental and test data, the sensor should operate with high stability for over 100 hours at 1093°C. Prototype 1 of this development program has been successfully operated for over 62 hours at 1093°C.

The extension of the sensing technique to other measurands has also been noted. Highly feasible designs are presented for extending the microphone sensing technique to measure acceleration, pressure and force.

12.0 RECOMMENDATIONS

It is the recommendation of the authors of this report that the present microphone system design be used for prototype production. This recommendation is based on the demonstrated performance and success of the completed program. The design of the prototype 2 sensor with the rhodium button is preferred since the more sensitive microphone can be used with a thicker diaphragm. Such a diaphragm will still assure an acceptable dynamic range but will increase the useable frequency band.

Other low-risk design options such as (1) a high temperature metallic sheathed cable consisting of platinum conductors and alumina insulation, (2) plasma spray coating and encapsulation of extension lead wires and (3) the use of a porous platinum filter plug are also recommended to be part of the design of any prototype production.

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